THE UNIVERSITY OF ALBERTA

FIELD EFFECT OF CUPROUS OXIDE

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled FIELD EFFECT OF CUPROUS OXIDE, submitted by THAVEESAKDI KEOWSIM in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

This thesis describes the basic principle of the field effect of semiconductors. It also describes experiments performed in order to determine the field effect of single crystals of cuprous oxide, which is known to be a p-type semiconductor. It is possible from measurements of the change in conductance of a bar of cuprous oxide semiconductor with application of an electric field normal to its surface to determine both the electrostatic potential of the surface and the distribution of charge in surface states. Such determinations depend upon the uniqueness of a minimum in surface conductance which is observed in these experiments. It must also be independent of the surface state charge.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Surfaces play an important role in a large range
of phenomena. Progress in our understanding of many of
the fundamental processes has been slow, however, and our
knowledge of the interface is far less extensive than of
the bulk. This is due in large measure to the fact that
the physical and chemical processes at the surface are
inherently more difficult to analyze. The bulk consists
of those regions of the crystal which may be looked upon
as an infinite, uniform periodic structure. At the surface,
on the other hand, the forces acting on the atoms are no
longer symmetrical so that even if the bulk is perfect in
every respect the surface atoms are usually displaced from
their ideal lattice positions, giving rise to a rather
complex two-dimensional structure. At the same time, the
unsaturated bonds of the surface atoms make them highly
reactive towards the various species outside the crystal.
All of these characteristics make the surface a totally
different entity from the bulk and require a high degree
of sophistication, both experimental and theoretical, for
its study.

The term surface or the equivalent term interface,
in its broad sense, describes any boundary region between
different media. Usually, however, one is primarily

interested in those boundaries in which the change in one or more of the properties characterizing each medium takes place over a region narrow compared to the spatial extent of the system considered. It is these abrupt boundaries that are generally identified with the surface or the interface. The most common interfaces are those separating any two of the solid, liquid, or gaseous phases in contact. Additional interfaces often occur, however, within each phase. In the solid these may be associated with the boundaries between crystallites of different crystallographic orientation, or between sections of different composition. Metal-semiconductor contacts and p-n junctions are important examples of such solid-solid interfaces. In the former case the two sections consist of entirely different substances, while in the latter the host crystal is the same and it is only the impurity distribution that varies across the interface.

One of the most important manifestations of the interface is the change in electrostatic potential associated with the transition from one medium to the other. In a semiconductor the potential variation may extend considerably into the underlying bulk, even if all other properties change abruptly. This accounts for the controlling effect of the interface on many of the electronic processes

in a semiconductor. From the experimental standpoint, such
a penetration is an invaluable asset in any quantitative
investigation of surface phenomena.

In this paper, the interfaces between a semicon-
ductor and a vacuum, gas, or liquid will be referred as
free surfaces or simply as surfaces, while the term inter-
face itself will be reserved for solid-solid systems.

1.1 Historical Notes[1]

The first reported phenomena directly related to
the field of semiconductor surfaces date back to the end
of the last century, when rectification effects were dis-
covered in 1874 by Braun in the system of a metal in con-
tact with a sulphide such as galena, and at about the same
time by Schuster[2] with copper-copper oxide contacts.
Shortly afterwards Adams and Day[3], working on selenium,
discovered the photovoltaic effect. The work at this stage
was largely empirical, involving much art and little under-
standing of the underlying physical principles.

In the early 1930's it became increasingly ap-
parent that rectification and photovoltaic effects were
intimately associated with the interface between a metal
and a semiconductor (or between two different semiconduc-
tors). It was also realized that these effects could arise
from the difference in work functions of the two solids.

In 1939 Schottky[4], Mott[5], and Davidov[6] independently formulated theories of rectification based on such considerations. The theories of Schottky, Mott, and Davidov were very successful in accounting quantitatively for the basic features of rectification, and they undoubtedly constituted a major advance in our understanding of interface phenomena. However, two very important links were missing in the theory, one pertaining to the origin of the space-charge region, the other concerning the role of the minority carriers in the current flow.

This group of puzzling phenomena was clarified in one stroke by the far-reaching hypothesis of Bardeen[7] in 1947 that the potential barrier at the semiconductor surface was produced by surface states rather than by contact potential between the semiconductor and the metal in contact with it. These states were assumed to be localized at the surface and to have energies in the otherwise forbidden energy gap. The possibility that localized states can exist at the surface had previously been pointed out by Tamm[8] and by Shockley[9] on purely theoretical grounds. Bardeen's idea was that electrons from the semiconductor interior can be trapped in the surface states, leaving behind an equal and opposite charge to maintain overall neutrality. Thus a space-charge region, and associated with it a potential barrier, form near the surface. If the den-

sity of surface states is sufficiently large, the potential
barrier remains essentially unaltered when contact is made
with a metal (or with another semiconductor). The main
work at that period was directed towards the investigation
of surface states on the one hand and of the detailed
characteristics of germanium point-contact rectifiers on
the other. It was in the course of this work that tran-
sistor action was discovered by Bardeen and Brattain[10].

       The existence of surface states on a free sur-
face was demonstrated by Shockley and Pearson[11], who were
also able to estimate their density, by a very direct
experiment. This, the field-effect experiment, has since
become one of the most important tools in surface studies.
In it a space-charge region is produced at the surface by
an externally applied electrostatic field in an analogous
way to the space charge set up by the proximity of a metal
of a different work function. A semiconductor slab was
used as one plate of a parallel plate capacitor, the other
plate being a metal electrode. By measuring the change in
conductance of the slab in a direction parallel to the
surface as a function of the voltage applied across the
capacitor, it was found that only a small fraction of the
total induced charge was mobile, indicating that most of
it is trapped in surface states.

In one experiment Brattain and Shockley[12] studied
the variation of contact potential between n- and p-type
samples as a function of bulk impurity content. In another
experiment Brattain[13] measured the change in contact poten-
tial upon illumination. These studies combined with care-
ful measurements of point-contact rectification character-
istics, brought to light the important role played in sur-
face phenomena by minority carriers, even when their concen-
tration in the bulk is very small. In an n-type semicon-
ductor, for example, the conductivity type may change from
n-type in the bulk to p-type at the surface, giving rise
to what is known as an inversion-type space-charge layer.

Following the discovery of transistor, the main
effort in semiconductor research shifted from surface phen-
omena to bulk properties. It was recognized that while
transistor action was primarily a bulk phenomenon, bulk
properties alone could not account for the anomalous be-
haviour of diodes and transistors and that many of the
spurious effects were associated with the surface. At the
same time, the availability of crystals of a high degree
of purity and lattice perfection, and the better under-
standing of bulk properties, made semiconductors an ideal
medium for surface studies.

1.2   Recent Developments in Surface Research

In the course of the surface studies of the last decade, it has become common to distinguish between two types of surfaces, real and clean. The former term refers to surfaces obtained by ordinary laboratory procedures, the latter to surfaces prepared under carefully controlled conditions so as to ensure minimal foreign matter.

Real surfaces have been studied extensively because they are easily prepared and handled and because they are readily amenable to many types of measurements. Moreover, it is the real surface that is encountered in most practical applications. Clean surfaces are much more difficult to produce. They can be prepared by cleavage, ion bombardment, or by heating at elevated temperatures. Once obtained, a clean surface must be maintained in ultra-high vacuum (10^{-10} to 10^{-9} mmHg) to slow down recontamination. The interest in clean surfaces stems from the fact that they constitute the closest approximation to the true crystal surface, and should thus exhibit the fundamental features of the surface per se.

The surface states observed on real surfaces (germanium and silicon) fall into two groups: the "fast states", which are presumably situated at the interface between the crystal and the oxide, and the "slow states",

located predominantly at the outer surface of the oxide layer and arising entirely from adsorbed gas atoms. The terms fast and slow refer to the relative speeds with which the respective states interact with the underlying space-charge region of the bulk crystal. The fast states are normally characterized by time constants of the order of microseconds or less, the slow states by time constants ranging from a fraction of a second to hours, depending on the structure of the oxide layer and the nature of the ambient gas. The fast states are usually present with a density of the order of 10^{11} cm^{-2} and their distribution in energy is essentially discrete. Regarding the slow states, little is known about their energy distribution and other characteristics besides the fact that under normal conditions their density is at least 10^{13} cm^{-2}. This density is sufficient to control the potential barrier at the surface.

The advances in the fundamental understanding of surface phenomena have contributed considerably to device technology. Most of the surface effects detrimental to device performance can be accounted for in terms of the characteristics of the space-charge layer and the surface states, and their known dependence on surface preparation and ambient gas.

While most of the efforts in device technology
are primarily aimed at the elimination of surface effects,
there is one notable example where interface phenomena are
specifically invoked for device operation. This is the
unipolar field-effect transistor. Recently, however, means
have been devised to nullify the effect of surface states
on certain structures involving silicon, cadmium sulphide
and gallium arsenide (Ga As). Such structures now play an
important role in semiconductor devices; including the input
transistors of high input impedance voltmeters such as used
for our experiments.

1.3   Scope of Our Work

The present work gives the basic principle of the
field-effect of semiconductors. Measurements of the field-
effect in cuprous oxide single crystals are reported. A
determination of the distribution of charge in surface
states is provided.

The presence of a minimum in the experimental
field-effect curve allowed us to compare the experimental
data with the calculated curves and to find the dependence
of the surface band curvature on the applied voltage.
Therefore for the analysis, we selected those samples for
which the dependence of the charge in the conductivity on
the applied voltage had a minimum.

The theoretical field-effect curves were calcu-
lated. The curves obtained and the values of the para-
meters used in the calculations are given. The dependence
of the band curvature V_s on the voltage applied to the
surface could be determined by comparing the theoretical
and experimental field-effect curves.

CHAPTER II

THEORY[1,14]

The physical processes that take place at the
surface of a semiconductor are greatly influenced by the
properties of the underlying bulk material. One can thus
hope to be able to separate surface and bulk effects only
by being well acquainted with bulk properties and by pos-
sessing a certain measure of control over them. A know-
ledge of bulk characteristics is also an essential pre-
requisite to surface studies from the conceptual aspect,
and in the present chapter we also introduce some of the
basic physics of semiconductors.

2.1   Occupation Statistics for Semiconductors (See Many et al[1])

We shall consider the actual distribution of
electrons and holes among the various energy states under
conditions of thermal equilibrium. The number of electrons
in any small energy interval at a fixed temperature depends
on two factors: the Fermi-Dirac distribution function,
which represents the probability of the electron having
this energy, and the number of available states in the
given energy interval.

2.1.1 <u>The Fermi-Dirac Distribution Law</u> (See Many et al[1])

Consider the quasi-free electrons in the allowed energy bands. The most probable energy distribution of an ensemble of this sort, being subject to the Pauli exclusion principle, is governed by Fermi-Dirac statistics. The probability that an energy level E be occupied at thermal equilibrium by an electron is given by the Fermi-Dirac distribution function

$$f_n(E) = \frac{1}{1 + \exp[(E - E_F)/kT]} \, , \qquad (1)$$

where E_F, referred to as the <u>Fermi level</u>, is determined by the requirement that the total expectation number of electrons be equal to the actual number of electrons involved. For $E = E_F$, $f = 1/2$, there being an equal probability that the level be occupied or vacant. The Fermi level is closely related to the thermodynamic or chemical potential and is a constant (at a given temperature) throughout a system in thermal equilibrium, even when the system is composed of different phases (such as occur in inhomogeneous semiconductors or in different materials in contact). The Fermi-Dirac distribution function is plotted in Fig. 1 and is seen to vary from unity at low energies to zero at high energies. The main change in occupation probability occurs in the neighbourhood of E_F, within an energy range $|E - E_F|$
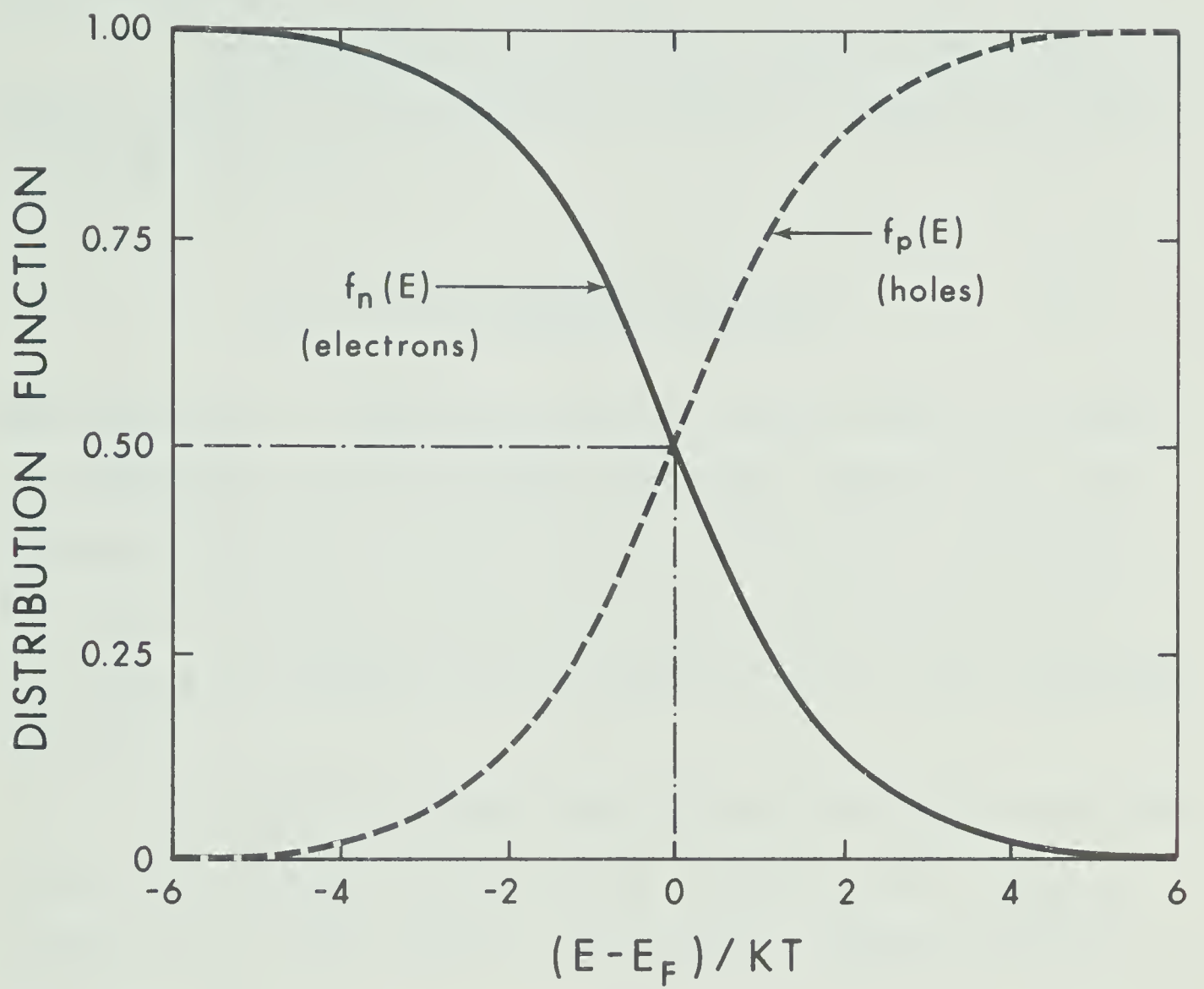
Figure 1. The Fermi-Dirac distribution functions $f_n(E)$ and $f_p(E)$ for electrons and holes.

of a few units of kT.

The probability $f_p(E)$ that a level E be vacant (that a positive hole occupy the level) is given by $f_p(E) = 1 - f_n(E)$; that is,

$$f_p(E) = \frac{1}{1 + \exp[(E_F - E)/kT]} \cdot \tag{2}$$

This function is represented by the dashed curve in Figure 1. Recalling that the energy for holes increases in the downward direction, we see that the distribution function for holes is identical with that for electrons provided the energy is measured (with respect to E_F) in the opposite direction.

In order to obtain the volume density of electrons $n(E)dE$ in an energy interval E, E + dE, we must multiply $f_n(E)$ by the volume density of available states $N(E)dE$ in this interval:

$$n(E)dE = f_n(E)N(E)dE. \tag{3}$$

The total density of electrons in the conduction band, n_b, is given by

$$n_b = \int_{E_C}^{E_C + A_C} N_C(E) f_n(E) dE, \tag{4}$$

where E_C and $E_C + A_C$ are the lower and upper edges of the conduction band, and $N_C(E)$ the density of states per unit

volume and unit energy in the band.

Similarly the total density of holes, p_b, in the valence band is given by

$$p_b = \int_{E_v - A_v}^{E_v} N_v(E) f_p(E) dE, \tag{5}$$

where $E_v - A_v$ and E_v are the lower and upper edges of the valence band, and $N_v(E)$ the density of states in the band. The subscript b in n_b and p_b stands for "bulk" and signifies that we are dealing with a homogeneous semiconductor.

When the Fermi level is well removed from either of the band edges, the distribution functions (1), (2) reduce to the classical Maxwell-Boltzmann expressions:

$$f_n(E) \simeq e^{-(E - E_F)/kT} = Ae^{-E/kT} \quad \text{for } (E - E_F) >> kT \tag{6}$$

$$f_p(E) \simeq e^{(E - E_F)/kT} = Be^{E/kT} \quad \text{for } (E_F - E) >> kT \tag{7}$$

where A and B are normalizing constants. This is only to be expected, since for $|E - E_F| >> kT$ the electron and hole densities are so low that the restrictions imposed by the Pauli exclusion principle are no longer significant. Under these conditions the semiconductor is said to be non-degenerate.

We now turn to the electrons distributed among the various <u>localized</u> states introduced into the forbidden gap by impurity and defect centres. The distribution law for such electrons depends on the characteristics of the centres. In general a centre can capture more than one electron, and in each charge condition there can be several available energy levels (ground and excited states). More-over, each state may be degenerate (such as when the centre can capture one electron of either spin). The occupation statistics for centres of this sort will be discussed later. Here we shall consider the simple case where, in the charge transfer process between each centre and the energy bands, only <u>one</u> electron takes part and the state of this electron is associated with a <u>single</u> energy level E_t. The proba-bility that such a centre be occupied by an electron is

$$f_n(E_t) = \frac{1}{1 + (g_o/g_1)\exp[(E_t - E_F)/kT]} \, , \qquad (8)$$

where g_o and g_1 represent the number of degenerate quantum states of the centre when it is vacant and occupied, res-pectively. If now we define an effective energy level E_t^f related to the actual level E_t by the equation

$$E_t^f = E_t + kT\ln(g_o/g_1) , \qquad (9)$$

then the distribution function [eq. (8)] reduces to that

for quasi-free electron [eq. (1)] with E_t replaced by E_t^f:

$$f_n(E_t^f) = \frac{1}{1 + \exp[(E_t^f - E_F)/kT]}. \tag{10}$$

E_t^f is sometimes called the free energy of the centre.

The density of occupied (n_t) and unoccupied (p_t) centres is given by

$$n_t = N_t f_n(E_t^f); \tag{11}$$

$$p_t = N_t f_p(E_t^f), \tag{12}$$

where $f_p(E_t^f)$ is defined similarly to $f_n(E_t^f)$, i.e.

$$f_p(E_t^f) = \frac{1}{1 + \exp[(E_F - E_t^f)/kT]}, \tag{13}$$

and $N_t = n_t + p_t$ is the total density of centres having an effective energy E_t^f. It should be noted that now the centres are half occupied ($n_t = p_t$) when the Fermi level coincides with E_t^f, rather than with E_t.

2.1.2 Intrinsic Semiconductors (See Many[1], Sze[14])

In a chemically pure semiconductor having no localized levels, the electron and hole densities must be equal, since every electron excited into the conduction band leaves behind a hole in the valence band. The carrier

densities in this case will be denoted by n_i:

$$n_i = n_b = p_b. \tag{14}$$

Applying this condition to (4) and (5), we can determine the Fermi level and thus obtain an expression for n_i. In a semiconductor the energy gap $E_g (\equiv E_c - E_v)$ is usually large compared to kT so that n_i will be sufficiently small to permit the use of Boltzmann statistics [eqs. (6), (7)]. Furthermore, electrons will be found only near the minimum (E_c) of the conduction band and holes near the maximum (E_v) of the valence band. In these regions the density of state $N_c(E)$, $N_v(E)$ can be expressed in terms of the components of the effective mass tensor[1]. For the case in which there is a single minimum in the conduction band and a single maximum in the valence band, the densities of states can be written in the form

$$N_c(E) = \left(\frac{4\pi}{h^3}\right)(2m_n)^{3/2}(E - E_c)^{1/2}; \tag{15}$$

$$N_v(E) = \left(\frac{4\pi}{h^3}\right)(2m_p)^{3/2}(E_v - E)^{1/2}. \tag{16}$$

Here m_n and m_p are given by $(m_x m_y m_z)^{1/3}$, where m_x, m_y, m_z represent the diagonal components of the effective-mass tensor for electron at E_c and for holes at E_v. If there

is a number of minima (or maxima), (15) and (16) should be replaced by appropriate sums over the various valleys. The average masses m_n and m_p appearing in (15) and (16) are referred to as the "density-of-states" effective masses.

The intrinsic carrier densities are obtained from (4) and (5) in conjunction with (6), (7), (15), and (16):

$$n_b = n_i = \left(\frac{4\pi}{h^3}\right)(2m_n)^{3/2} \int_{E_c}^{E_c + A_c} (E - E_c)^{1/2} e^{-(E - E_F)/kT} dE;$$
(17)

$$p_b = n_i = \left(\frac{4\pi}{h^3}\right)(2m_p)^{3/2} \int_{E_v - A_v}^{E_v} (E_v - E)^{1/2} e^{(E - E_F)/kT} dE.$$
(18)

Because of the rapidly decreasing exponentials under the integral signs, the limits of integration $E_c + A_c$ and $E_v - A_v$ can be replaced by $+\infty$ and $-\infty$, respectively. Consequently

$$n_b = n_i = N_c e^{-(E_c - E_F)/kT};$$
(19)

$$p_b = n_i = N_v e^{-(E_F - E_v)/kT}.$$
(20)

where

$$N_c \equiv 2\left(\frac{2\pi m_n kT}{h^2}\right)^{3/2};$$
(21)

$$N_V \equiv 2\left(\frac{2\pi m_p kT}{h^2}\right)^{3/2}. \qquad (22)$$

Hence, for the purpose of calculating the carrier densities, the conduction and valence bands can be regarded as two single levels at energies E_C and E_V having effective densities of states N_C and N_V, respectively. From (19) and (20) we have that

$$n_i^2 = N_C N_V e^{-(E_C - E_V)/kT} = N_C N_V e^{-E_g/kT} \qquad (23)$$

The intrinsic Fermi level, $E_F^{(i)}$, is given by

$$E_F^{(i)} = (1/2)(E_C + E_V) - (1/2)kT\ln(N_C/N_V). \qquad (24)$$

If the density-of-states effective masses for electrons and holes are equal, then $N_C = N_V$ and $E_F^{(i)}$ lies exactly midway between the conduction- and valence-band edges. In most semiconductors the deviation from this position is small, since the difference in mass enters only logarithmically into the expression for $E_F^{(i)}$.

2.1.3 Semiconductors with Localized Levels (See Many[1], Sze[14])

We turn now to consider the effect of impurity or defect centres on the carrier densities. Evidently, as long as non-degenerate conditions prevail, the electron

and hole densities will still be given by (19) - (22), so
that

$$n_b = N_c e^{-(E_c - E_F)/kT} \text{ for } (E_c - E_F) >> kT, \qquad (25)$$

$$p_b = N_v e^{-(E_F - E_v)/kT} \text{ for } (E_F - E_v) >> kT. \qquad (26)$$

The Fermi level is no longer given by (24) but now depends
on the density and energy distribution of the localized
levels in the forbidden gap. On the other hand, the pro-
duct $n_b p_b$ depends, as before, on temperature only:

$$n_b p_b = N_c N_v e^{-E_g/kT} = n_i^2. \qquad (27)$$

Non-degenerate conditions, for which eqs. (25) - (27) have
been derived, will be assumed to hold throughout the sub-
sequent discussions.

In some semiconductors the carrier densities are
usually controlled by the introduction of shallow impurity
levels. Consider then, a semiconductor having a concen-
tration N_D of shallow donors at energy E_D just below E_c and
a concentration N_A of shallow acceptor at energy E_A just
above E_v. The density of electrons n_D bound to donors and
of holes p_A bound to acceptors can be expressed in terms
of the respective effective energies E_D^f and E_A^f [see eqs.
(9) - (13)] in the form

$$n_D = \frac{N_D}{1 + \exp[(E_D^f - E_F)/kT]} \; ; \qquad (28)$$

$$p_A = \frac{N_A}{1 + \exp[(E_F - E_A^f)/kT]}. \qquad (29)$$

The Fermi level is determined by the condition of overall electrical neutrality. The density of the negative charge is $-q(n_b + N_A - p_A)$ while that of the positive charge is $q(p_b + N_D - n_D)$. Thus

$$n_b + n_D + N_A = p_b + p_A + N_D. \qquad (30)$$

Using (25), (26), (28) and (29), we obtain from (30) a quadratic equation in $\exp(E_F/kT)$ which, in the general case, must be solved numerically.

Consider an intrinsic semiconductor and introduce into it a few shallow donors whose ionization energy $E_C - E_D$ is small compared to the forbidden gap. As long as N_D is not too large compared to n_i, E_F will not depart appreciably from its intrinsic position [eq. (24)] and will remain well below E_D. Use of (25) and (28) then yields

$$n_D/n_b = (N_D/N_C) e^{(E_C - E_D^f)/kT} \qquad (31)$$

and thus $n_D \ll n_b$. It therefore follows from the neutrality

condition [eq. (30)] that $n_b - p_b = N_D$, the donors being in effect completely ionized. Combining this condition with the relation $n_b p_b = n_i^2$ [eq. (27)], we obtain

$$n_b = (1/2) N_D \left[\left(1 + \frac{4n_i^2}{N_D^2} \right)^{1/2} + 1 \right]; \qquad (32)$$

$$p_b = (1/2) N_D \left[\left(1 + \frac{4n_i^2}{N_D^2} \right)^{1/2} - 1 \right]. \qquad (33)$$

Obviously n_b is greater than p_b, and we have what is called an n-type semiconductor. For $N_D \gg n_i$ the electrons originating from the donors far exceed those excited across the gap, and $n_b \sim N_D$. Under these conditions the electron density is essentially a constant, independent of temperature, and we have an extrinsic n-type semiconductor. And the position of Fermi level is now given by (see eq. (25)]

$$(E_c - E_F)/kT = \ln(N_c/N_D). \qquad (34)$$

The assumption of non-degeneracy made above is valid for $N_D \lesssim 0.1 N_c$.

Referring to (31), $E_c - E_D^f$ may no longer be small compared to kT (in the range of very low temperatures) and full ionization will not take place. Equations (32) and

(33) are then no longer valid and we must use the Fermi-Dirac distribution function to describe the density of the electron bound to donors. For sufficiently low temperatures

$$n_b = \sqrt{N_c N_D} \; e^{(E_c - E_D^f)/2kT} \quad \text{for } E_c - E_D >> kT \qquad (35)$$

and

$$E_F = (1/2)(E_c + E_D^f) - (1/2)kT\ln(N_c/N_D). \qquad (36)$$

These equations are identical with (23) and (24) for an intrinsic semiconductor provided that E_v and N_v are replaced by E_D^f and N_D.

We can now see how the free-carrier density in a given semiconductor varies with temperature. This is illustrated in Figure 2 for an n-type semiconductor ($N_D >> N_A$). Here $\ln n_b$ is plotted again $1/T$, and three ranges are apparent. A very low temperature (35) holds, n_b increasing exponentially with T. The slope in this range yields the ionization energy $E_c - E_D$. As the temperature is raised extrinsic conditions are approached, and thereafter n_b is a constant (equal to $N_D - N_A$) over a considerable temperature range. At still higher temperatures, carrier excitation across the forbidden gap becomes important and (32), (33) are applicable. At sufficiently high temperature such that $n_i >> N_D - N_A$, intrinsic conditions set in and n_b
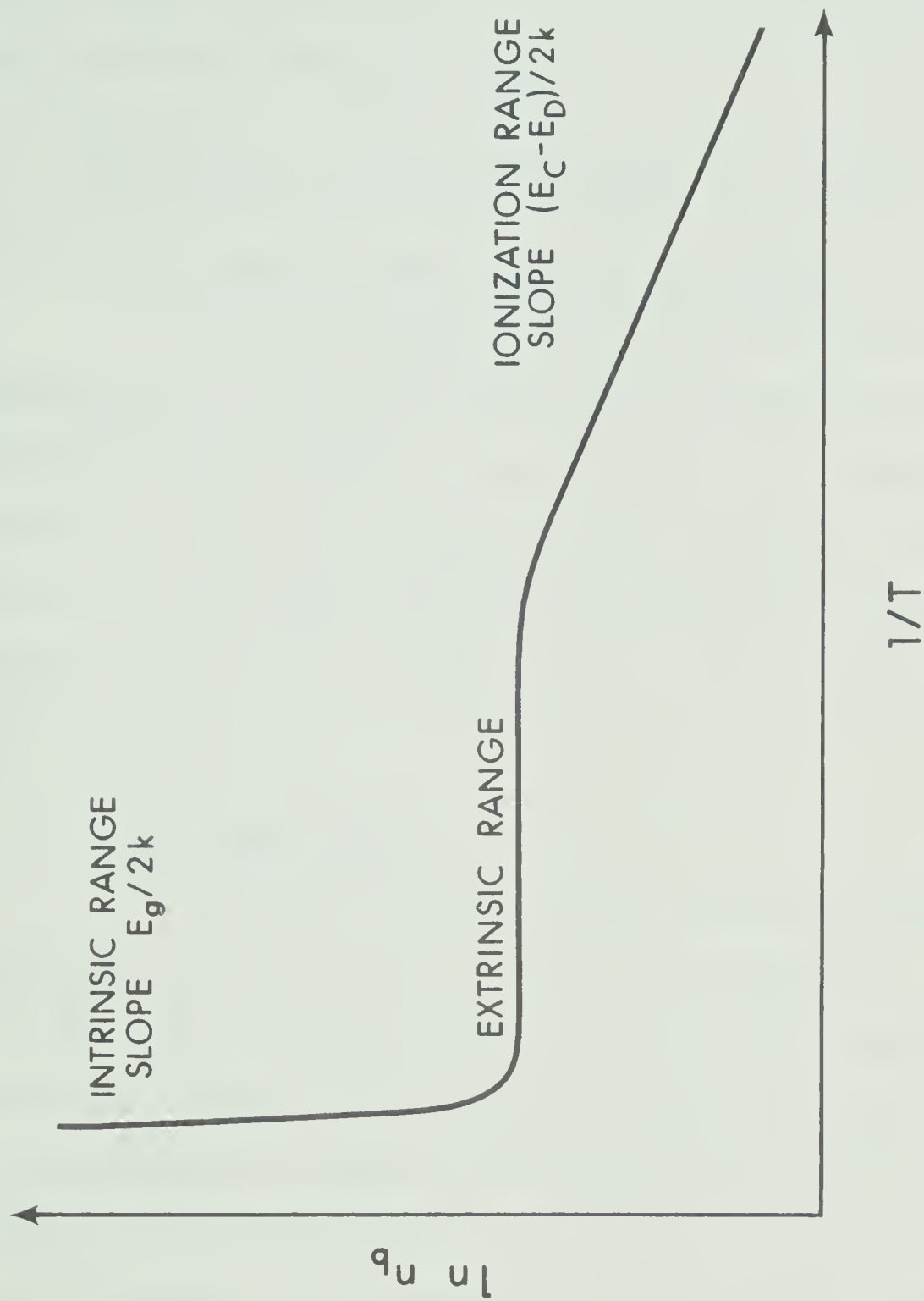
Figure 2. Temperature variation of the electron density in an n-type semiconductor.

again varies exponentially with T [eq. (23)]. The slope
now yields the energy gap E_g.

2.2 The Surface Space-Charge Region (See Many et al[1])

2.2.1 The Origin of the Space-Charge Region

The space-charge region near the surface of a
conducting solid may be produced by an external applied
electric field outside the solid, or by the proximity of
another solid with a different work function. Alterna-
tively, it may result from the presence of a localized
charged layer at the surface proper, due usually to sur-
face states.

2.2.1.1 External Field

Consider a parallel-plate capacitor having one
electrode a metal and the other a semiconductor. The ap-
plication of a voltage across the capacitor results in
the establishment of an electric field E between the plates.
A displacement of mobile charge-carriers near the surface
of each plate takes place, thus giving rise to two space
charge regions. The density Q_S of the induced charge on
each plate is given by Gauss law:

$$Q_S = \epsilon_o E. \tag{37}$$

Since the free carrier density in a semiconductor is much

smaller than that in a metal, the space-charge region will

extend much farther into the bulk of the former. This

situation is illustrated schematically in Figure 3. In

order to obtain an idea of the magnitude of the total

potential drop V_s between the surface and the underlying

bulk, we shall approximate the potential in the space-

charge region by a linear extension (dashed line). From

the figure we see that

$$\frac{V_s}{V_o - V_s} = \frac{Z_s / \varepsilon_s}{Z_o} \tag{38}$$

where V_o is the applied voltage, Z_o is the separation of

the capacitor plates and Z_s the approximate distance

(within the semiconductor) over which the potential drops

to zero. An estimate of Q_s is readily obtained by Gauss'

law

$$Q_s = \frac{-\varepsilon_o (V_o - V_s)}{Z_o} \approx q n_b Z_s . \tag{39}$$

Combining (38) and (39) we have

$$Z_s \approx \sqrt{\frac{\varepsilon_o \varepsilon_s |V_s|}{n_b q}} \quad ; \quad \frac{V_s}{V_o - V_s} \approx \frac{\varepsilon_o (V_o - V_s)}{\varepsilon_s Z_o^2 n_b q} . \tag{40}$$

The approximations used in deriving eq. (40) appear rather

crude, nevertheless the results yield the correct order of

Figure 3. Potential distribution in the space-charge region. [Space-charge region in an n-type semiconductor devoid of surface states as produced by an applied voltage between a metal and the semiconductor. The potential and electron energy are shown as functions of the normalized distance Z/ε. The three curves are for different values of the bulk electron density n_b, the uppermost curve corresponding to the smallest n_b. The dots illustrate the electron energy distribution in the semiconductor.]
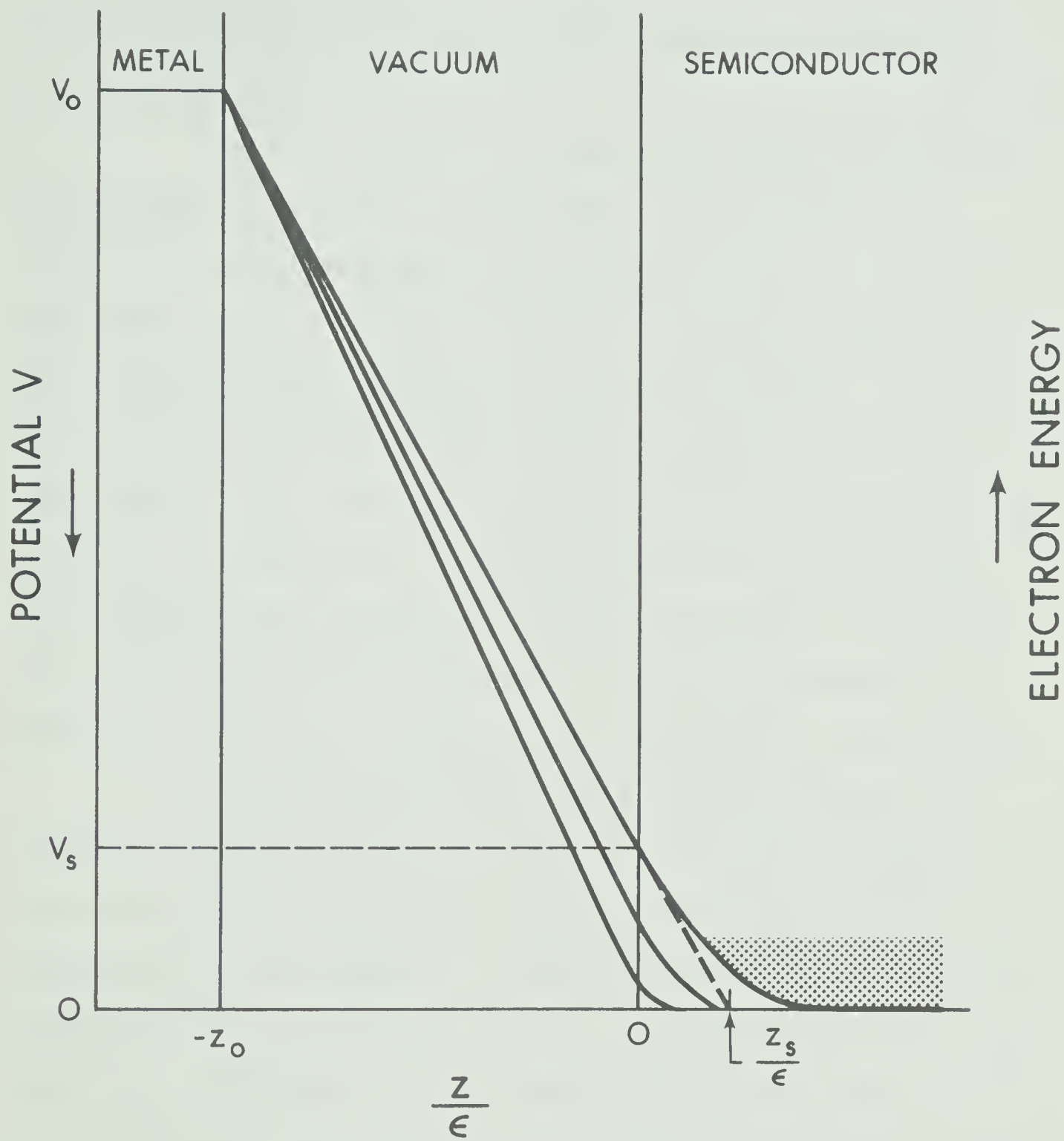
magnitude..

2.2.1.2 Contact Potential and the Metal-Semiconductor
        Contact

        The work required to remove an electron at the

Fermi level to a point in free space just outside the

solid is defined as the work function W_ϕ of the solid. In

semiconductors it is found useful to define a second quan-

tity, the electron affinity X, as being the work required

to remove an electron from the bottom edge of the conduc-

tion band at the surface to a point in free space just out-

side the semiconductor. The work function and affinity

are illustrated in Figure 4a, which represents an energy-

level diagram for an electron in a system composed of a

metal and an n-type semiconductor separated by free space.

        We now make an electrical contact between the

solids in such a way as to allow the flow of electrons from

one medium to the other but without disturbing the surfaces

presented in the figure. In the case illustrated, the work

function of the semiconductor W_ϕ' is lower than that of the

metal W_ϕ. Electrons in the semiconductor thus tend to flow

into the metal and a space charge builds up at the two sur-

faces. This flow continues until the Fermi levels are

adjusted to the same height, corresponding to thermal

equilibrium conditions, as shown in Figure 4b. Because
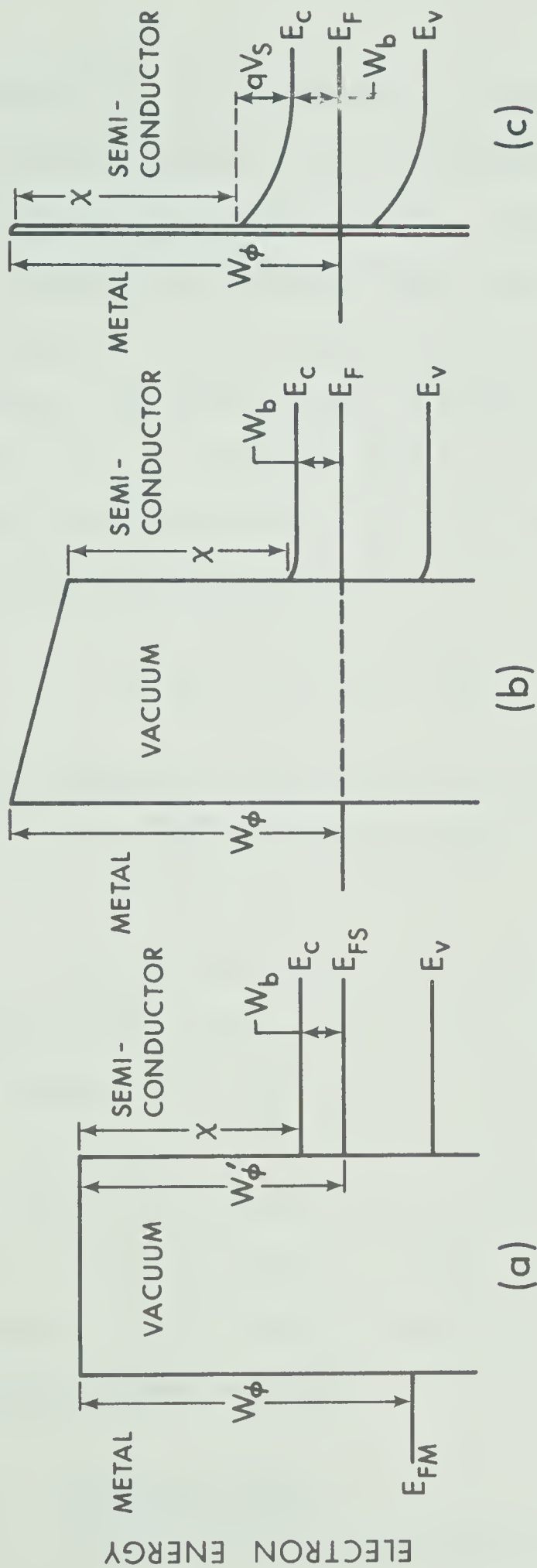
Figure 4. Energy-level diagram for an electron in a metal and an
n-type semiconductor devoid of surface states. The two
media are

(a) isolated from one another,

(b) in thermal equilibrium, and

(c) in close proximity.

the separation of the metal and the semiconductor is large,
the contact potential (the difference in work functions)
falls mostly across the vacuum. Accordingly, the energy
bands of the semiconductor bend only slightly upwards, cor-
responding to a small space charge. As the separation
decreases, the bending of the bands increases until, the
surfaces are at atomic distance (as Figure 4c), practically
the whole contact potential falls across the space-charge
region and V_s is given by

$$-qV_s = W_\phi - W_\phi' = W_\phi - X - W_b. \qquad (41)$$

Here W_b represents the energy difference between the Fermi
level E_F and conduction-band edge E_c in the semiconductor
bulk.

It follows from (41) that V_s depends on the work
function of the metal and on the affinity. Contrary to
these theoretical expectations, experimental evidence has
shown that V_s is usually practically independent of the
metal and of the conductivity of the semiconductor. To
explain this discrepancy, Bardeen[7] proposed the existence
of surface states--energy levels in the forbidden gap at
the semiconductor surface.

2.2.1.3 Surface States

In the absence of surface states, the energy

bands of a semiconductor continue straight up to the sur-
face, provided there is no external field. When acceptor-
like surface states are introduced below the Fermi level,
they will not be in equilibrium with the energy bands as
long as they remain unoccupied. This situation is illus-
trated in Figure 5a, where the surface states have been
introduced at an energy level E_t. Since the states are
empty and below the Fermi level, some of the electrons in
the conduction band fall into them. In this process, the
surface becomes negatively charged while a positive space-
charge layer forms below it. Consequently, the energy
bands at the surface bend upwards with respect to the Fermi
level. The process of charge transfer continues until
equilibrium is reached (Figure 5b). In the particular case
shown, the surface states at thermal equilibrium are some-
what above the Fermi level and so are only partially filled.
The larger the surface-state density, the higher the bend-
ing of the bands at the surface. The situation for donor-
like surface states placed above the Fermi level is com-
pletely analogous (Figure 5c, 5d). The introduction of
acceptor-like states above the Fermi level or of donor-
like states below the Fermi level has of course no influence
on the shape of the energy bands.

Now consider the modification that the presence
of surface states introduces into the treatment of the
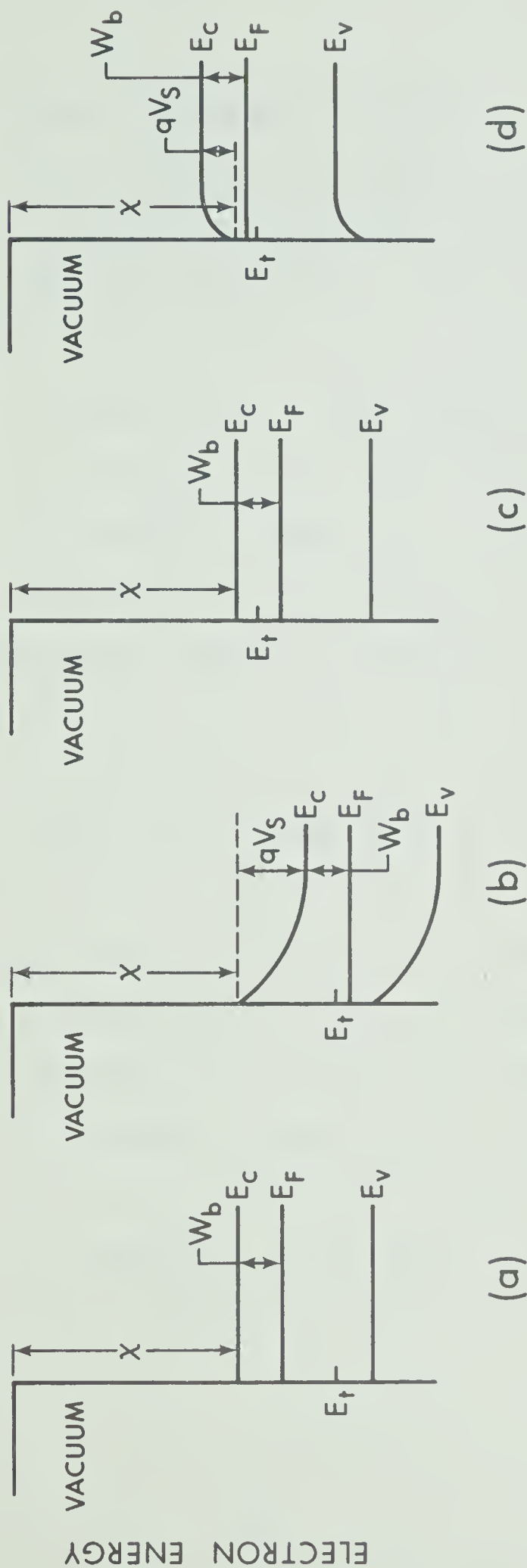
Figure 5. Energy-level diagram for an n-type semiconductor in the presence of acceptor-like [(a) and (b)] and donor-like [(c) and (d)] surface states at an energy level E_t.

(a) and (c) represent conditions immediately following the introduction of the surface states; (b) and (d), after thermal equilibrium has been reached.

metal-semiconductor contact. If such states are appropriately located with respect to the Fermi level, the energy bands will be bent even before any electrical contact is made with the metal. Figure 6a illustrates this situation for the case of a large density of charged acceptor-like surface states. When thermal equilibrium is established and the two Fermi levels coincide, the energy bands of the semiconductor bend only slightly higher (Figure 6b). This slight additional bending is sufficient to cause the required number of electrons to leave the surface states and enter the metal. Thus, the field caused by the contact potential is almost entirely terminated by the surface states rather than by the space charge, and nearly the whole contact potential falls across the vacuum. This situation continues as the metal-semiconductor separation is decreased to a few interatomic distances (Figure 6c), provided the surface-state density is sufficiently large. The barrier height V_s then remains practically independent of the work functions of the solids, and the system behaves as though the semiconductor surface were a thin metallic film screening the bulk from external fields.
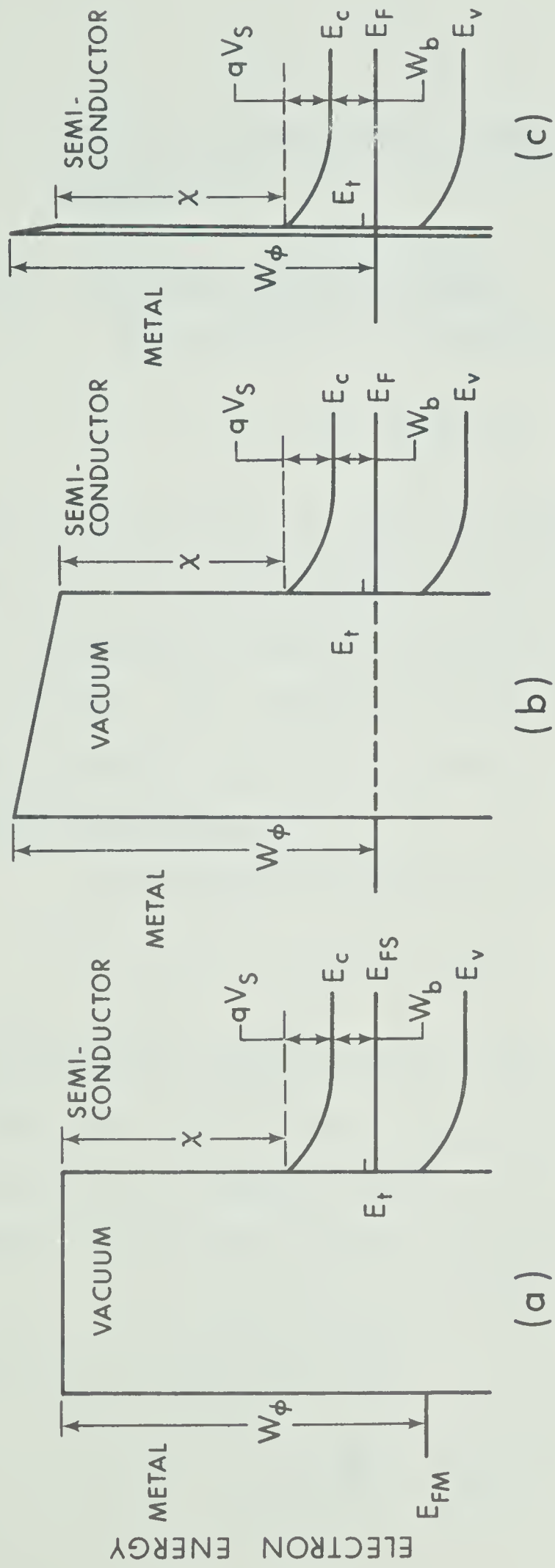
Figure 6. The effect of (acceptor-like) surface states on the metal-semiconductor contact.

(a) Prior to electrical contact.

(b) After thermal equilibrium has been reached.

(c) At close proximity.

2.2.2 The Space-Charge Density and the Potential Barrier

(See Many[1])

2.2.2.1 Concepts and Definitions

The potential ϕ is defined by the equation

$$q\phi \equiv E_F - E_i, \tag{42}$$

where E_i is parallel to the band edges and in the bulk coincides with the intrinsic Fermi level (Figure 7). Its exact position is given by (24), and is usually close to the mid-gap. The value of ϕ in the bulk is called the bulk potential, ϕ_b, and its value at the surface, the surface potential, ϕ_s.

The potential barrier V is defined as

$$V \equiv \phi - \phi_b \tag{43}$$

and represents the potential at any point in the space-charge region with respect to its value in the bulk. In particular the barrier height V_s ($\equiv \phi_s - \phi_b$) is the total potential difference between the surface and the bulk.

It is convenient to define dimensionless potentials u, v by the equations

$$u \equiv \frac{q\phi}{kT} = \frac{E_F - E_i}{kT} ; \tag{44}$$
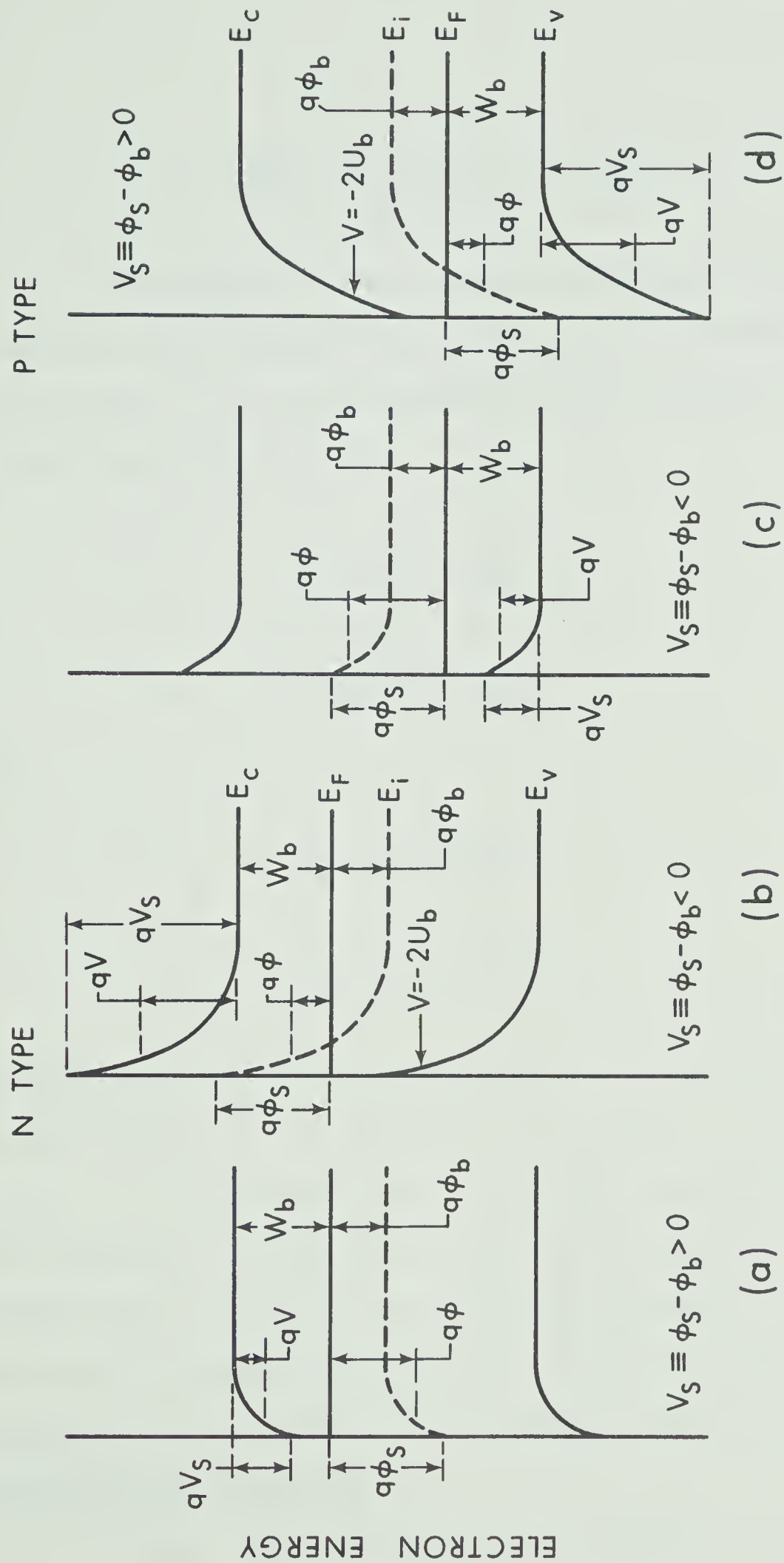
Figure 7. Energy-level diagram indicating the various energy parameters used to characterize the space-charge region,

(a) n-type semiconductor, accumulation layer. (b) Inversion layer.

(c) p-type semiconductor, accumulation layer. (c) Inversion layer.

N TYPE

(a) $V_S \equiv \phi_S - \phi_b > 0$

(b) $V_S \equiv \phi_S - \phi_b < 0$

ELECTRON ENERGY

E_c, W_b, $q\phi_b$, qV, $q\phi$, E_v, qV_S, $q\phi_S$

E_c, qV_S, qV, $q\phi$, W_b, E_F, E_i, $q\phi_b$, $V = -2U_b$, E_v, $q\phi_S$

P TYPE

(c) $V_S \equiv \phi_S - \phi_b < 0$

(d) $V_S \equiv \phi_S - \phi_b > 0$

$q\phi_b$, W_b, $q\phi$, qV, $q\phi_S$, qV_S

E_c, $q\phi_b$, E_i, E_F, W_b, E_v, $V = -2U_b$, $q\phi$, $q\phi_S$, qV_S, qV

$$v \equiv \frac{qV}{kT} = \frac{q(\phi \cdot \phi_b)}{kT} = u - \frac{q\phi_b}{kT} . \tag{45}$$

By means of the intrinsic carrier concentration n_i and the above definitions, the electron density n and hole density p in a non-degenerate semiconductor are given at every point by

$$n = n_i e^u = n_b e^v ; \tag{46}$$

$$p = n_i e^{-u} = p_b e^{-v} , \tag{47}$$

where

$$n_b = n_i e^{q\phi_b/kT} ,$$

$$\tag{48}$$

$$p_b = p_i e^{-q\phi_b/kT} .$$

The condition $u > 0$ signifies that at that point $n > p$, and conversely; $v > 0$ implies $n > n_b$ and $p < p_b$, and con-versely. At the point where $u = 0$ the carrier densities are intrinsic; in particular $u_b = 0$ corresponds to an in-trinsic bulk, $u_s = 0$ to an intrinsic surface. When $v_s = 0$ there is no bending of the energy bands and they continue straight from the bulk to the surface. This is known as the _flat-band_ condition.

When the majority-carrier density in the space-

charge region is greater than that in the bulk, the space-charge region is termed an <u>accumulation</u> layer. This condition obtains when the sign of v_s is the same as that of u_b [eqs. (46), (47)]: positive for n-type and negative for p-type. When the sign of v_s is opposite to that of u_b, we have either a <u>depletion</u> or an <u>inversion</u> layer. The space-charge region up to the point where the minority carrier density equals the majority-carrier bulk density ($v = -2u_b$) is called the <u>depletion region</u>. Between this point and the surface the minority-carrier density exceeds the majority-carrier bulk density, and this region is called the <u>inversion region</u>. Figure 7 illustrates the above definitions for an n- and p-type semiconductor.

2.2.2.2 <u>Poisson's Equation</u>[1,14,15,16]

We shall derive the relations between the surface potential, space charge, and electric field in this subsection.

Figure 8 shows a more detailed band diagram at the surface of a p-type semiconductor. The potential V is defined as zero in the bulk of the semiconductor, and is measured with respect to the intrinsic Fermi level E_i as shown. At the semiconductor surface $V = V_s$, and V_s is called the surface potential. The electron and hole concentrations as functions of V are given by the following
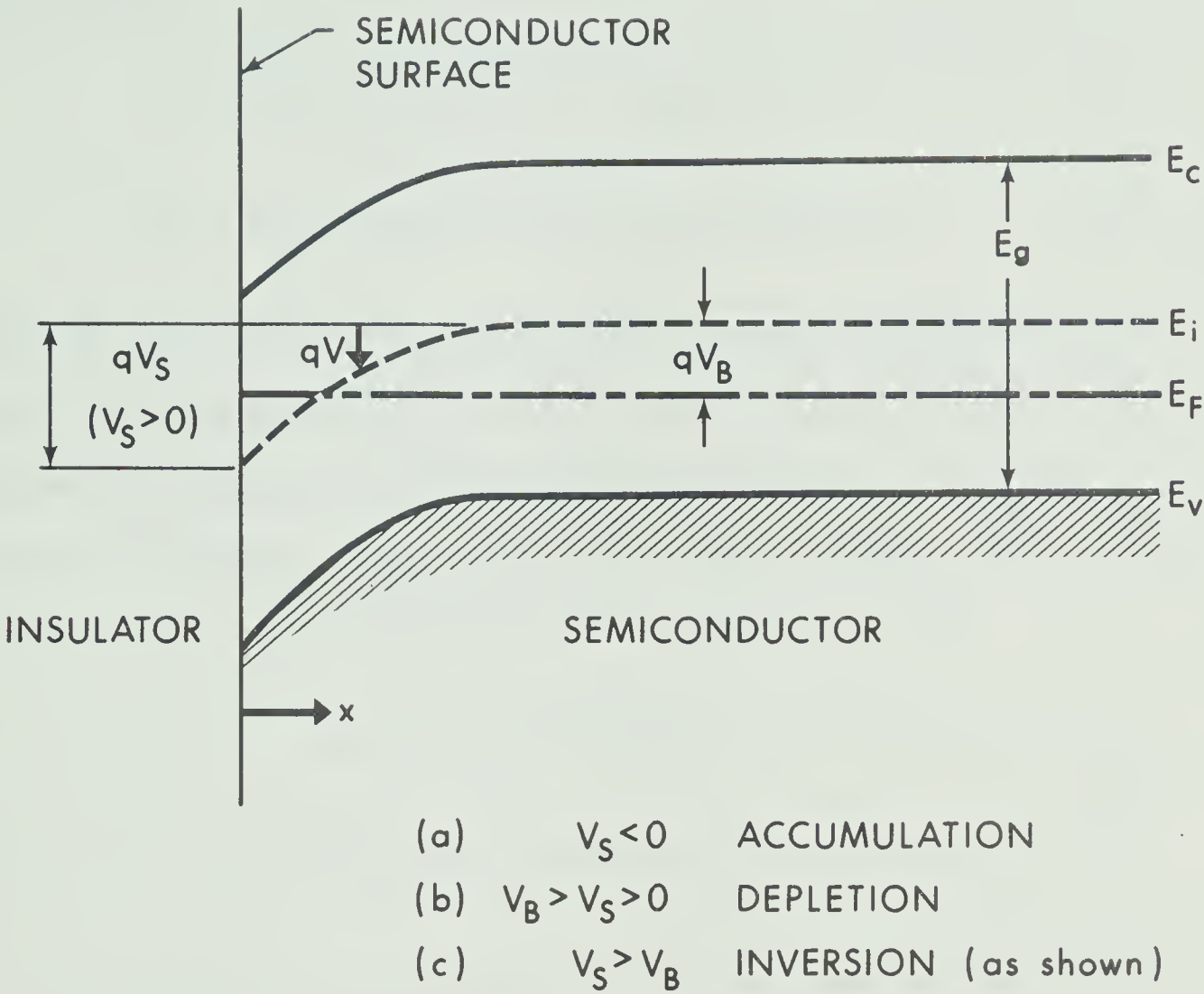
Figure 8. Energy band diagram at the surface of a p-type semiconductor. The potential V is defined as zero in the bulk and is measured with respect to the intrinsic Fermi level E_i. V_s is the surface potential and is positive as shown.

relations:

$$n_p = n_{po} \exp(qV/kT) = n_{po} \exp(\beta V); \qquad (49)$$

$$p_p = p_{po} \exp(-qV/kT) = p_{po} \exp(-\beta V), \qquad (50)$$

where V is positive when the band is bent downward (as shown in Figure 8), n_{po} and p_{po} are the equilibrium densities of electrons and holes respectively in the bulk of the semiconductor [$n_{po} = n_b$, $p_{po} = p_b$, in eqs. (46), (47)], and $\beta \equiv q/kT$. At the surface the densities are

$$n_s = n_{po} \exp(\beta V_s),$$

$$\qquad (51)$$

$$p_s = p_{po} \exp(-\beta V_s).$$

It is obvious from the previous discussions and with the help of eq. (51) that the following regions of surface potential can be distinguished:

$V_s < 0$ Accumulation of holes (bands bend upward),

$V_s = 0$ Flat-band condition,

$V_B > V_s > 0$ Depletion of holes (bands bend downward),

$V_s = V_B$ Midgap with $n_s = p_s = n_i$ (intrinsic concentration),

$V_s > V_B$ Inversion (electron enhancement, bands bend downward).

The potential V as a function of distance can be obtained by using the one-dimensional Poisson equation

$$\frac{\partial^2 V}{\partial X^2} = \frac{-\rho(X)}{\varepsilon_o \varepsilon_s} \qquad (52)$$

where ε_s is the permittivity of the semiconductor (or the dielectric constant of the semiconductor) and $\rho(X)$ is the total space-charge density given by

$$\rho(X) = q(N_D^+ - N_A^- + p_p - n_p) \qquad (53)$$

where N_D^+ and N_A^- are the densities of the ionized donors and acceptors respectively. Now, in the bulk of the semi-conductor, far from the surface, charge neutrality must exist. Therefore $\rho(X) = 0$ and $V(X) = 0$, when $X \rightarrow \infty$, and we have

$$N_D^+ - N_A^- = n_{po} - p_{po} \qquad (54)$$

In general for any value of V, we have from eqs. (49) and (50)

$$p_p - n_p = p_{po}e^{-\beta V} - n_{po}e^{\beta V}. \qquad (55)$$

The resultant Poisson's equation to be solved is therefore

$$\frac{\partial^2 V}{\partial X^2} = \frac{-q}{\varepsilon_o \varepsilon_s}\left[p_{po}(e^{-\beta V} - 1) - n_{po}(e^{\beta V} - 1)\right]. \qquad (56)$$

Integration of eq. (56) from the bulk toward the surface[17]

$$\int_0^{\frac{\partial V}{\partial X}}\left(\frac{\partial V}{\partial X}\right)d\left(\frac{\partial V}{\partial X}\right) = \frac{-q}{\varepsilon_o \varepsilon_s}\int_0^V [p_{po}(e^{-\beta V} - 1) - n_{po}(e^{\beta V} - 1)]dv, \qquad (57)$$

gives the relation between the electric field $\left[E \equiv -\dfrac{\partial V}{\partial X}\right]$ and the potential V:

$$E^2 = \left(\frac{2kT}{q}\right)^2\left(\frac{qp_{po}\beta}{2\varepsilon_o \varepsilon_s}\right)\left[(e^{-\beta V} + \beta V - 1) + \frac{n_{po}}{p_{po}}(e^{\beta V} - \beta V - 1)\right].$$
$$(58)$$

We shall introduce the following abbreviation:

$$L_D \equiv \sqrt{\frac{2kT\varepsilon_o \varepsilon_s}{p_{po}q^2}} \equiv \sqrt{\frac{2\varepsilon_o \varepsilon_s}{qp_{po}\beta}}, \qquad (59)$$

and

$$F\left(\beta V, \frac{n_{po}}{p_{po}}\right) \equiv \left[(e^{-\beta V} + \beta V - 1) + \frac{n_{po}}{p_{po}}(e^{\beta V} - \beta V - 1)\right]^{1/2} \geqslant 0,$$
$$(60)$$

where L_D is called the extrinsic Debye length for holes.
Thus the electric field becomes

$$E = -\frac{\partial V}{\partial X} = \pm\frac{2kT}{qL_D} F\left(\beta V, \frac{n_{po}}{p_{po}}\right) \qquad (61)$$

with positive sign for $V > 0$ and negative sign for $V < 0$.
To determine the electric field at the surface, we let $V = V_s$:

$$E_s = \pm \frac{2kT}{qL_D} F\left(\beta V_s, \frac{n_{po}}{p_{po}}\right)$$

(62)

$$= \pm \left(\frac{2kTp_{po}}{\varepsilon_o \varepsilon_s}\right)^{1/2} \left[(e^{-\beta V_s} + \beta V_s - 1) + \frac{n_{po}}{p_{po}}(e^{\beta V_s} - \beta V_s - 1)\right]^{1/2}.$$

Similarly, by Gauss' law the space charge per unit area
required to produce this field is

$$Q_s = \varepsilon_o \varepsilon_s E_s = \stackrel{-}{+} \frac{2\varepsilon_o \varepsilon_s kT}{qL_D} F\left(\beta V_s, \frac{n_{po}}{p_{po}}\right)$$

(63)

$$= \stackrel{-}{+}(2\varepsilon_o \varepsilon_s kTp_{po})^{1/2} [(e^{-\beta V_s} + \beta V_s - 1) + \frac{n_{po}}{p_{po}}(e^{\beta V_s} - \beta V_s - 1)]^{1/2}$$

with negative sign for $V_s > 0$ and positive sign for $V_s < 0$.

2.2.3 The Excess Surface-Carrier Densities Δn and Δp

The excess surface-carrier densities are defined
as the number (per unit surface area) of mobile electrons
Δn and holes Δp in the space-charge layer with respect to
their number at flat bands. It should be noted that if Δn
is positive then Δp is negative, and conversely. To deter-
mine the change in hole density, Δp, and electron density,

Δn, per unit area when the potential V at the surface is shifted from zero to a final value V_s, it is necessary to evaluate the following expression[18]:

$$\Delta p = \int_0^\infty (p_p - p_{po})\,dx = p_{po}\int_0^\infty (e^{-\beta V} - 1)\,dx$$

$$= \frac{qL_D p_{po}}{2kT} \int_{V_s}^0 \frac{(e^{-\beta V} - 1)\,dv}{F\left(\beta V, \dfrac{n_{po}}{p_{po}}\right)} \tag{64}$$

$$\Delta n = \int_0^\infty (n_p - n_{po})\,dx = n_{po}\int_0^\infty (e^{\beta V} - 1)\,dx \tag{65}$$

$$= \frac{qL_D n_{po}}{2kT} \int_{V_s}^0 \frac{(e^{\beta V} - 1)\,dv}{F\left(\beta V, \dfrac{n_{po}}{p_{po}}\right)} = \frac{qL_D p_{po}}{2kT}\left[\frac{n_{po}}{p_{po}}\int_{V_s}^0 \frac{(e^{\beta V} - 1)\,dv}{F\left(\beta V, \dfrac{n_{po}}{p_{po}}\right)}\right].$$

It should be noted that, in terms of these quantities, the surface space-charge density Q_s [in eq. (63)] can be expressed as

$$Q_s = q(\Delta p - \Delta n). \tag{66}$$

2.2.4 Surface Conductance, $\Delta\sigma$ (See Many et al[1])

The surface conductance $\Delta\sigma$ at any barrier height V_s is defined as the change in sample conductance per square area of its surface resulting from a change in bar-

rier height from 0 to V_s. For a homogeneous sample of uniform cross section, we have

$$\Delta\sigma = \frac{\ell^2}{A}\left(\frac{1}{R} - \frac{1}{R_o}\right).\tag{67}$$

Here A is the total surface area parallel to the direction of current flow, ℓ is the sample length, R is the sample resistance, and R_o is the value of R at $V_s = 0$. If we assume that the carrier mobilities in the space-charge layer are the same as those in the bulk then evidently

$$\Delta\sigma = q(\mu_n \Delta n + \mu_p \Delta p)$$

$$= q\mu_p(\Delta p + \frac{\mu_n}{\mu_p}\Delta n)\tag{68}$$

$$= q\mu_p(\Delta p + b\Delta n)$$

$$=\left(\frac{q}{kT}\right)\cdot\left(\frac{\varepsilon_o\varepsilon_s kT}{2}P_{po}\right)^{\frac{1}{2}}\mu_p\int_{V_s}^{0}\frac{[(e^{-\beta V} - 1) + b\left(\frac{n_{po}}{P_{po}}\right)(e^{\beta V} - 1)]dv}{[(e^{-\beta V} + \beta V - 1) +\left(\frac{n_{po}}{P_{po}}\right)(e^{\beta V} - \beta V - 1)]^{\frac{1}{2}}}$$

where $b = \frac{\mu_n}{\mu_p}$ = mobility ratio, μ_n is the electron mobility and μ_p is the hole mobility.

The dependence of surface conductance on barrier height can be seen from eq. (68). Conversely, if the surface conductance can be measured, it may be used to derive

the corresponding value of barrier height[17,18,19]. It is
apparent that both accumulation and inversion layers are
characterized by high conductances. In accumulation layers
this is due to the large number of majority carriers, in
inversion layers to the large number of minority carriers.
The surface conductance is less in depletion layers and
passes through a minimum value $\Delta\sigma_{min}$ where very few mobile
carriers are present in the space-charge region. The exact
value V_{sm} of the barrier height at which the minimum occurs
can be evaluated by differentiating (68). We then obtain[1]

$$v_{sm} = \frac{qV_{sm}}{kT} \simeq -2u_b - \ln\left(\frac{\mu_n}{\mu_p}\right). \qquad (69)$$

In order to determine the surface conductance,
the sample is provided with two non-rectifying end con-
tacts and its resistance is measured while the potential
barrier is varied by external means. Obviously the maxi-
mum in sample resistance corresponds to the minimum in
surface conductance $\Delta\sigma_{min}$. As can be seen from (69), the
value v_{sm} for which this occurs is a unique (and known)
function of temperature and impurity concentration.

2.3 Surface States[1,14,15,20]

The surface states have been theoretically stu-
died by Tamm[8], Shockley[9] and others[21,22] and have been

shown to exist within the forbidden gap due to the inter-
ruption of the periodic lattice structures at the surface
of a crystal. The existence of surface states was first
found experimentally by Shockley and Pearson[11] in their
surface conductance measurement. Surface states have been
classified into fast and slow states. The fast states
exchange charge with the conduction or valence band rapidly,
and are assumed to lie close to the interface between the
semiconductor and the insulator. Slow states, on the other
hand, exist at the interface of the air and insulator and
require a longer time for charge exchange.

2.3.1 Occupation Statistics of Single-Charge Surface States[1]

Consider the simplest case, that in which each
centre at the surface can capture or release only one
electron, thereby introducing a single allowed energy level
E_t in the forbidden gap. All centers are assumed to have
identical characteristics and to be present with a density
(N_t) that is sufficiently low to eliminate any mutual
interaction. The equilibrium densities of occupied (n_t)
and unoccupied ($p_t \equiv N_t - n_t$) centres are given by Fermi-
Dirac statistics in terms of energy position of the sur-
face states with respect to the Fermi level at the surface,
in a manner analogous to that in section (2.1.3). Now,

however, N_t, n_t, p_t refer to densities per unit area. As in the case of bulk states, we introduce an effective energy level E_t^f [eq. (9)] to allow for possible multiplicity of the surface states. Recalling, further, that at the surface [see section (2.2.2.1)]

$$(E_t^f - E_F)/kT = (E_t^f - E_i)/kT - u_s \qquad (70)$$

(u_s being the surface potential), we have that

$$n_t/N_t = f_n(E_t^f) \; ;$$

$$\qquad (71)$$

$$p_t/N_t = f_p(E_t^f) ,$$

where the Fermi distribution functions $f_n(E_t^f)$ and $f_p(E_t^f)$ are given by

$$f_n(E_t^f) = \frac{1}{1 + \exp[(E_t^f - E_i)/kT - u_s]} \; ;$$

$$\qquad (72)$$

$$f_p(E_t^f) = \frac{1}{1 + \exp[u_s - (E_t^f - E_i)/kT]} \; .$$

From (70) - (72) we see that when $u_s = (E_t^f - E_i)/kT$, then $n_t = p_t = 1/2\,N_t$. The main change in occupation takes place within a few units of u_s; the steepest slope occurs at $f_n(E_t^f) = 1/2$ and is equal to 1/4.

In general, we can expect the surface to have several such independent levels at energies E_{tj} and of densities N_{tj}. In this case the density of electrons captured in all surface states will be given by the sum $\sum_j N_{tj} f_n(E_{tj}^f)$.

2.3.2 The Variation of Surface Potential with External Field

The value of the surface potential in the absence of an external electric field is determined by the density and energy distribution of the surface states. The neutrality condition requires that

$$Q_{ss}^o + Q_s^o = 0;$$

Q_{ss} is the charge density (per unit area) in the surface states and is equal to $-qn_t$ for acceptor-like states and $+qp_t$ for donor-like states, and Q_s is the space-charge density as defined in section (2.2.2.2). The superscript "o" indicates the absence of an external field. By substituting for n_t, p_t, Q_s from (71) and (63), we obtain

$$\frac{2\varepsilon_o \varepsilon_s kT}{q^2 L_D} F\left(\beta V_s, \frac{n_{po}}{p_{po}}\right) = N_t f(E_t^f) \tag{73}$$

where the distribution function $f(E_t^f)$ represents $f_n(E_t^f)$
for acceptor-like states and $f_p(E_t^f)$ for donor-like states.
It is seen that for large surface state densities

$$N_t >> \frac{2\varepsilon_o \varepsilon_s kT}{q^2 L_D} \, ,$$

E_t^f will be removed from E_F and donor-like states will remain
relatively full and acceptor-like states relatively empty.
In general, u_s (or v_s) will be determined by several levels
of this type, and then in place of $N_t f(E_t^f)$ there will appear
in (73) the sum $\sum_j N_{tj} f(E_{tj}^f)$ over all surface levels present.

We shall now see how the surface potential changes
under the effect of an external electrostatic field applied
normal to the surface. For such a case we obtain that

$$Q_{ss} + Q_s = Q_T,$$

where Q_T is the total charge induced by the field. This
equation expresses the fact that the induced charge Q_T is
distributed between the surface states and the space-charge
region. Under equilibrium conditions we have, similarly
to (73), that

$$\mp \frac{2\varepsilon_o \varepsilon_s kT}{q^2 L_D} F\left(\beta V_s, \frac{n_{po}}{p_{po}}\right) \mp N_t f(E_t^f) = \frac{Q_T}{q} \, . \tag{74}$$

Here the upper sign before the second term (minus) refers
to acceptor-like states and the lower sign (plus) to donor-
like states. As for the first term, its sign is actually
that of Q_S (negative for $V_s > 0$, positive for $V_s < 0$).
Equation (74), which determines the new value of the sur-
face potential, is difficult to solve in the general case.
Experimentally, one usually measures Q_S and Q_T and in this
way determines the surface-state density.

2.4   D. C. Field Effect

The d. c. field effect consists of the steady-
state changes in surface conductance induced by electro-
static fields. For each applied field the system is al-
lowed to reach equilibrium and the sample resistance is
measured when no further change in its value is detectable.
The measuring voltage across the sample is kept small com-
pared to that applied at the field plate so as to maintain
the entire surface at effectively the same potential. It
is known that the geometric capacitance C_g is usually much
smaller than the surface capacitance C_s^{1}. The total charge
density Q_S induced at the semiconductor surface is then
practically independent of the barrier height and is given
by

$$Q_T = C_g V_A,$$

where V_A is the voltage applied at the field plate. The induced charge is distributed between the space-charge region and the surface states, giving rise to changes δQ_S and δQ_{ss} in the free and trapped charge densities, respectively:

$$Q_T = \delta Q_S + \delta Q_{ss}. \tag{75}$$

The change in resistance that one measures results almost entirely from δQ_S [or Q_S as in eq. (63)], the mobility of the carriers in the surface states being normally orders of magnitude lower than that of the free carriers in the space-charge region. If the range of variation in sample resistance can be made to include the maximum value R_M, then the barrier height V_s can be determined for each value of applied field. Since for a given semiconductor (and temperature) δQ_S [or Q_S] is a known function of V_s [eq. (63)], the trapped charge δQ_{ss} can be evaluated from (75) as a function of V_s. By comparing these results with the theoretical expression for the occupation statistics (see section 2.3.1), one can determine, at least in principle, the density and energy distribution of the various surface states[23]. This procedure is straightforward only if the distribution of the surface states is discrete and if the dominant sets of states are widely separated in

energy.   Otherwise the comparison does not yield the dis-
tribution in a unique manner.

It should be noted that in the case being con-
sidered--d. c. fields and steady-state conditions--all the
surface states participate, whatever their time constants.
Thus on real surfaces of semiconductors, charge is trapped
in both the fast and the slow states. The slow states,
however, are usually present with a much higher density
than the fast states, so that they will completely domin-
ate the trapping process.

Care should be taken in measurements to maintain
the sample at a constant temperature. The changes in sur-
face conductance are typically of the order of 1% of the
overall sample conductance.

CHAPTER III

THEORETICAL CALCULATIONS

3.1 Theoretical Calculation of the Space-Charge Density, Q_s, and the Electric Field at the Surface, E_s, as the Functions of the Surface Potential, V_s.

Using equations (62) and (63), the theoretical calculations of Q_s, E_s as a function of V_s were made and the results are given graphically in Figures 9, 10, 11, and 12.

The values of parameters of Cu_2O in our calculations are as the following:

at room temperature, $T = 300°K$ (deg),

$$\varepsilon_o = 8.85 \times 10^{-12} \text{ farad/meter},$$

$$k = 1.38 \times 10^{-23} \text{ Joule/deg},$$

$$kT = 0.026 \text{ ev},$$

$$q = 1.6 \times 10^{-19} \text{ coulomb},$$

$$\beta = \frac{q}{kT} = 38.46 \text{ V}^{-1},$$

$$\varepsilon_s = 7.5 \text{ [for } Cu_2O],$$

$$p_o = 1.26 \times 10^{20} \text{ m}^{-3} = 1.26 \times 10^{14} \text{ cm}^{-3}, \text{[24,25,26,27]}$$

$$n_o = 7.45 \times 10^{-2} \text{ m}^{-3} = 7.45 \times 10^{-8} \text{ cm}^{-3}, \text{[24,25,26,27]}$$

Therefore, $$\left(\frac{n_o}{p_o}\right) = 5.9 \times 10^{-22},$$

$$(2kT\varepsilon_s\varepsilon_o p_o)^{1/2} = 1.25 \times 10^{-6} \text{ coulomb/m}^2,$$

and
$$\left(\frac{2kTp_o}{\varepsilon_s \varepsilon_o}\right)^{1/2} = 1.25 \times 10^5 \text{ volt/m.}$$

The calculations were done on the PDP-8E computer and the numerical results are presented in Tables 1, 2, 3 and 4.
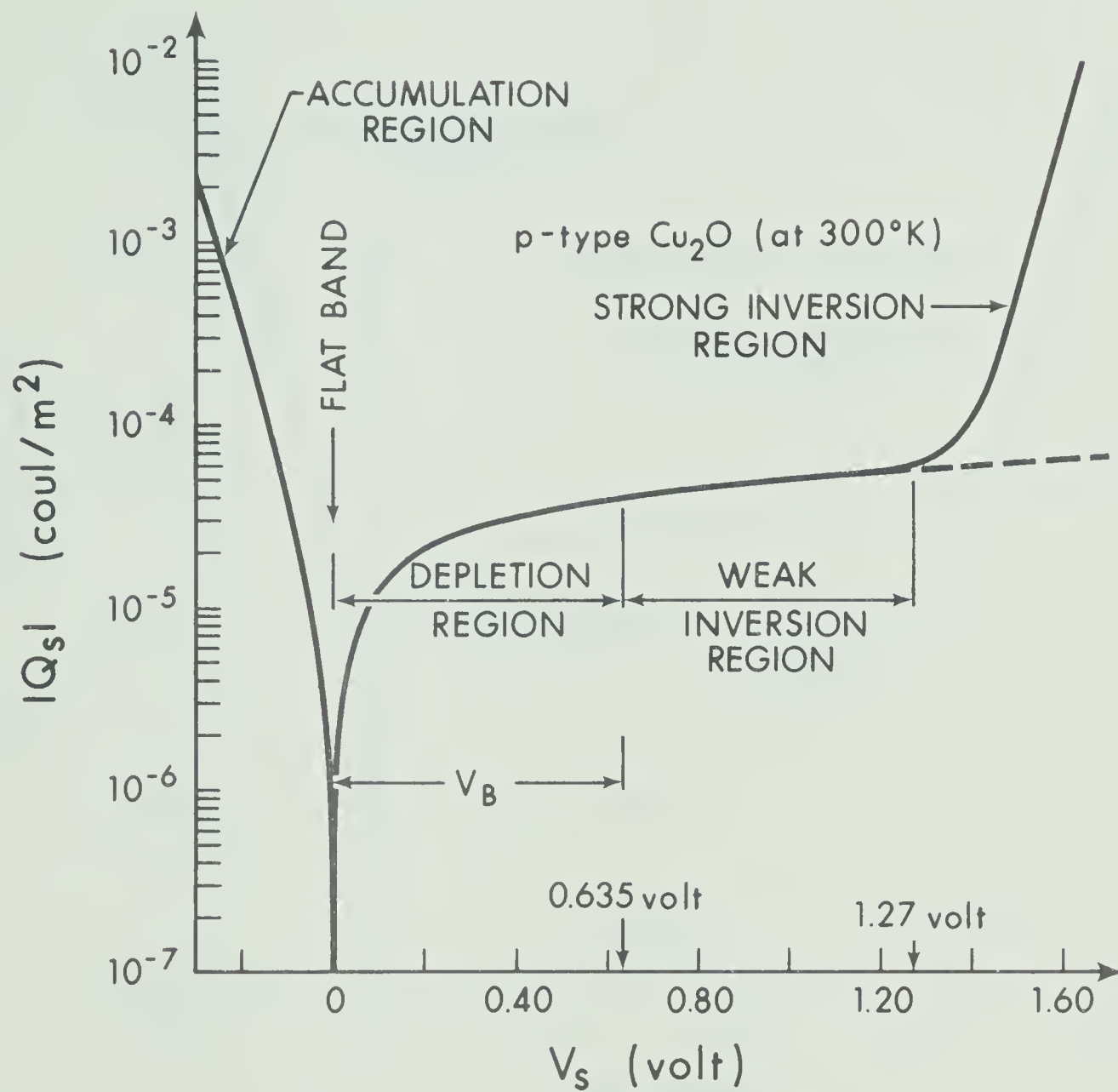
Figure 9. Theoretical curve of $|Q_s|$ vs V_s with $|Q_s|$ in coul/m^2.
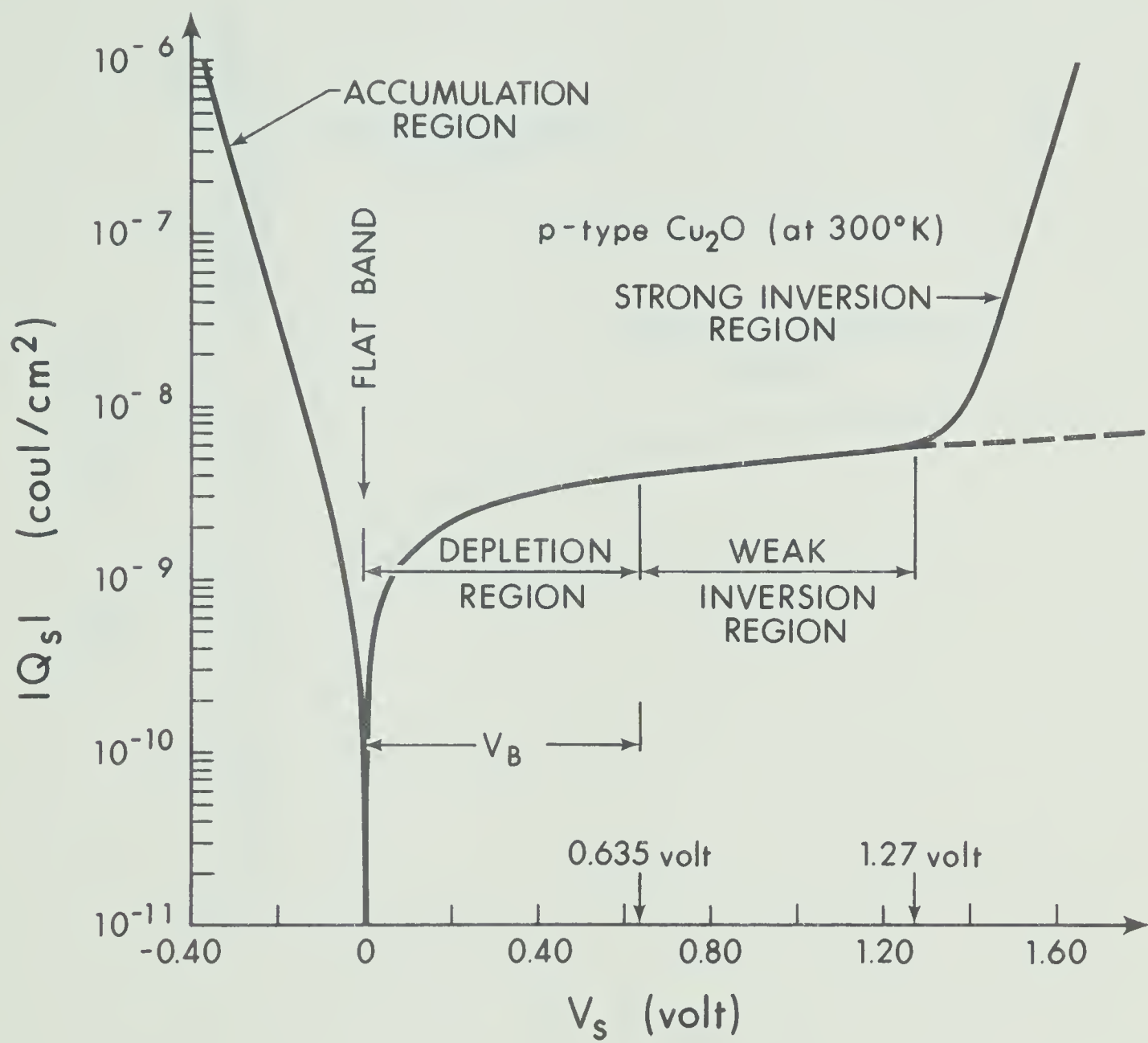
Figure 10. Theoretical curve of $|Q_s|$ vs V_s with $|Q_s|$ in coul/cm^2.
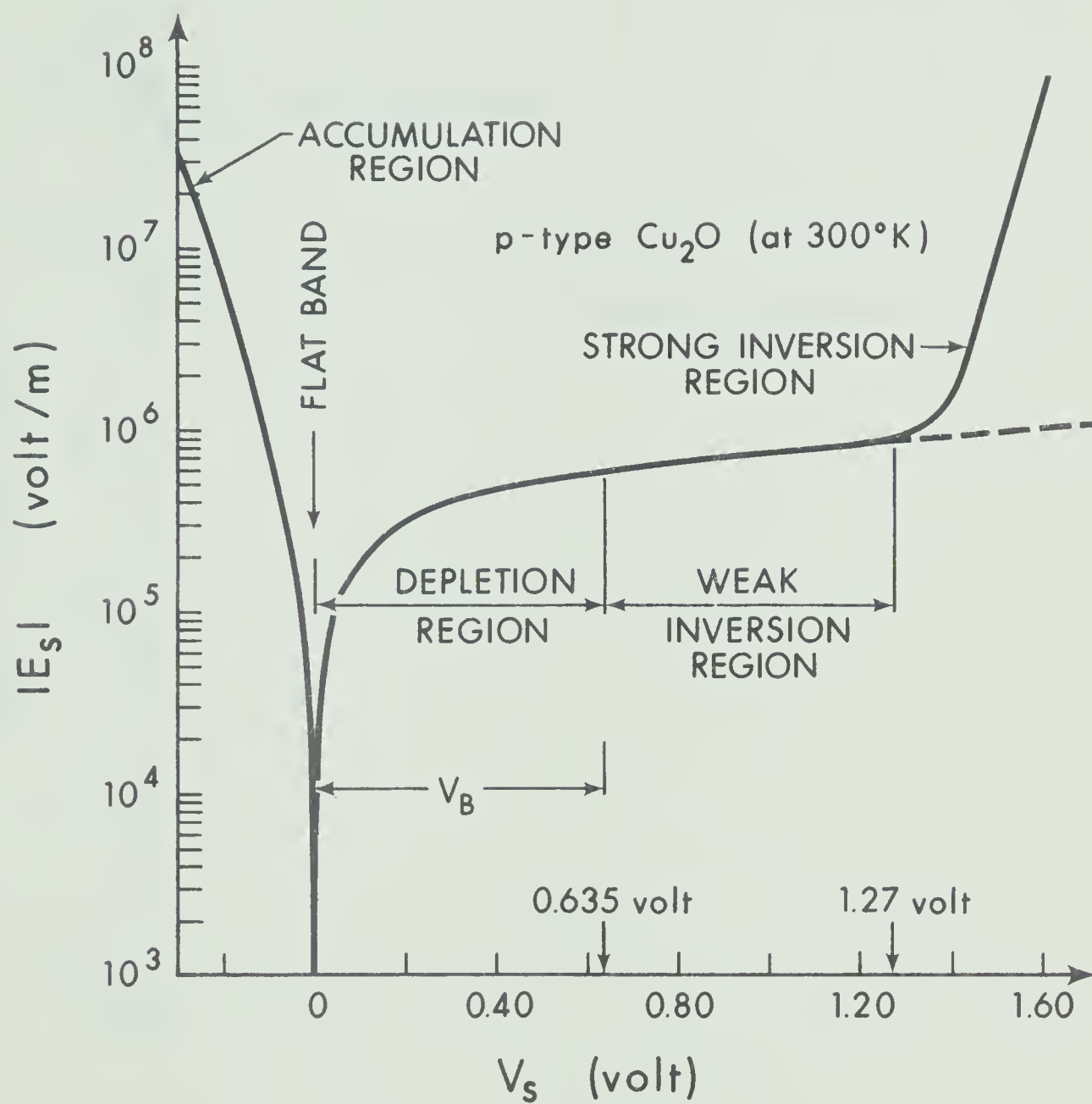
Figure 11. Theoretical curve of $|E_s|$ vs V_s with $|E_s|$ in volt/m.
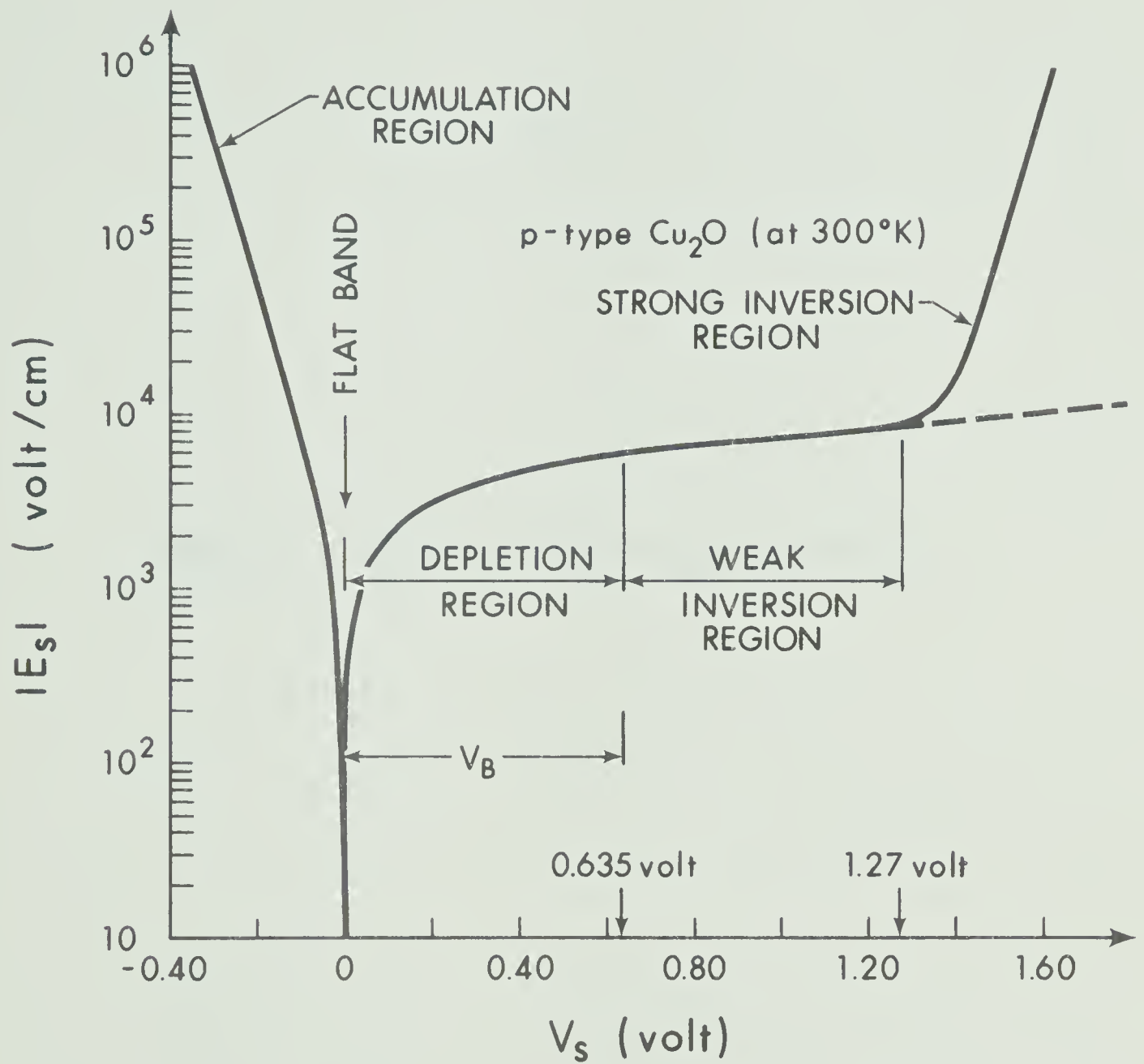
Figure 12. Theoretical curve of $|E_s|$ vs V_s with $|E_s|$ in volt/cm.

Table 1. Relation between Q_s, E_s and V_s.

```
C-FOCAL,1969

01.01 FOR V=0.00,0.05,2.00; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=6.64E-11
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET Q=A*FSQT(D+5.9E-22*G)
02.07 SET X=Q/B
02.08 TYPE %3.02,V," ", %,-Q," ", %,-Q*1E-4," ", %,X," ", %,X*1E-2,!
*GO
```

V_s (volt)	Q_s (coul/m²)	Q_s (coul/cm²)	E_s (volt/m)	E_s (volt/cm)
0.00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.05	-0.860292E-05	-0.860292E-09	0.129562E+06	0.129562E+04
0.10	-0.140885E-04	-0.140885E-08	0.212176E+06	0.212176E+04
0.15	-0.181752E-04	-0.181752E-08	0.273723E+06	0.273723E+04
0.20	-0.215236E-04	-0.215236E-08	0.324151E+06	0.324151E+04
0.25	-0.244204E-04	-0.244204E-08	0.367777E+06	0.367777E+04
0.30	-0.270086E-04	-0.270086E-08	0.406756E+06	0.406756E+04
0.35	-0.293697E-04	-0.293697E-08	0.442315E+06	0.442315E+04
0.40	-0.315546E-04	-0.315546E-08	0.475220E+06	0.475220E+04
0.45	-0.335977E-04	-0.335977E-08	0.505990E+06	0.505990E+04
0.50	-0.355235E-04	-0.355235E-08	0.534993E+06	0.534993E+04
0.55	-0.373562E-04	-0.373562E-08	0.562503E+06	0.562503E+04
0.60	-0.390916E-04	-0.390916E-08	0.588729E+06	0.588729E+04
0.65	-0.407586E-04	-0.407586E-08	0.613835E+06	0.613835E+04
0.70	-0.423601E-04	-0.423601E-08	0.637954E+06	0.637954E+04
0.75	-0.439032E-04	-0.439032E-08	0.661193E+06	0.661194E+04
0.80	-0.453939E-04	-0.453939E-08	0.683644E+06	0.683644E+04
0.85	-0.468372E-04	-0.468372E-08	0.705380E+06	0.705380E+04

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
= 0.90 =	-0.482373E-04	= -0.482373E-08	= 0.726466E+06	= 0.726466E+04
= 0.95 =	-0.495979E-04	= -0.495979E-08	= 0.746957E+06	= 0.746957E+04
= 1.00 =	-0.509222E-04	= -0.509222E-08	= 0.766900E+06	= 0.766901E+04
= 1.05 =	-0.522130E-04	= -0.522130E-08	= 0.786340E+06	= 0.786340E+04
= 1.10 =	-0.534733E-04	= -0.534733E-08	= 0.805321E+06	= 0.805321E+04
= 1.15 =	-0.547090E-04	= -0.547090E-08	= 0.823930E+06	= 0.823930E+04
= 1.20 =	-0.559468E-04	= -0.559468E-08	= 0.842572E+06	= 0.842572E+04
= 1.25 =	-0.573544E-04	= -0.573544E-08	= 0.863771E+06	= 0.863771E+04
= 1.30 =	-0.600256E-04	= -0.600256E-08	= 0.904000E+06	= 0.904000E+04
= 1.35 =	-0.705022E-04	= -0.705022E-08	= 0.106178E+07	= 0.106178E+05
= 1.40 =	-0.116399E-03	= -0.116399E-07	= 0.175299E+07	= 0.175299E+05
= 1.45 =	-0.267316E-03	= -0.267316E-07	= 0.402584E+07	= 0.402584E+05
= 1.50 =	-0.683271E-03	= -0.683271E-07	= 0.102902E+08	= 0.102902E+06
= 1.55 =	-0.178078E-02	= -0.178078E-06	= 0.268190E+08	= 0.268190E+06
= 1.60 =	-0.465532E-02	= -0.465532E-06	= 0.701103E+08	= 0.701103E+06
= 1.65 =	-0.121756E-01	= -0.121756E-05	= 0.183367E+09	= 0.183367E+07
= 1.70 =	-0.318461E-01	= -0.318461E-05	= 0.479609E+09	= 0.479609E+07
= 1.75 =	-0.832967E-01	= -0.832967E-05	= 0.125447E+10	= 0.125447E+08
= 1.80 =	-0.217872E+00	= -0.217872E-04	= 0.328121E+10	= 0.328121E+08
= 1.85 =	-0.569866E+00	= -0.569866E-04	= 0.858232E+10	= 0.858232E+08
= 1.90 =	-0.149055E+01	= -0.149055E-03	= 0.224481E+11	= 0.224481E+09
= 1.95 =	-0.389874E+01	= -0.389874E-03	= 0.587160E+11	= 0.587160E+09
= 2.00 =*	-0.101975E+02	= -0.101975E-02	= 0.153577E+12	= 0.153577E+10

Table 2. Relation between Q_s, E_s and V_s.

```
C-FOCAL,1969

01.01 FOR V=0.00,0.01,1.75; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=6.64E-11
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET Q=A*FSQT(D+5.9E-22*G)
02.07 SET Y=Q/B
02.08 TYPE %3.02,V," ", %,-Q," ", %,-Q*1E-4," ", %,Y," ", %,Y*1E-2,!
*GO
```

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
0.00	= 0.000000E+00	= 0.000000E+00	= 0.000000E+00	= 0.000000E+00
0.01	= -0.212645E-05	= -0.212645E-09	= 0.320248E+05	= 0.320248E+03
0.02	= -0.401248E-05	= -0.401248E-09	= 0.604289E+05	= 0.604289E+03
0.03	= -0.569926E-05	= -0.569926E-09	= 0.858323E+05	= 0.858323E+03
0.04	= -0.722032E-05	= -0.722032E-09	= 0.108740E+06	= 0.108740E+04
0.05	= -0.860292E-05	= -0.860292E-09	= 0.129562E+06	= 0.129562E+04
0.06	= -0.986928E-05	= -0.986928E-09	= 0.148634E+06	= 0.148634E+04
0.07	= -0.110375E-04	= -0.110375E-08	= 0.166228E+06	= 0.166228E+04
0.08	= -0.121224E-04	= -0.121224E-08	= 0.182566E+06	= 0.182566E+04
0.09	= -0.131361E-04	= -0.131361E-08	= 0.197832E+06	= 0.197832E+04
0.10	= -0.140885E-04	= -0.140885E-08	= 0.212176E+06	= 0.212176E+04
0.11	= -0.149879E-04	= -0.149879E-08	= 0.225721E+06	= 0.225721E+04
0.12	= -0.158410E-04	= -0.158410E-08	= 0.238570E+06	= 0.238570E+04
0.13	= -0.166536E-04	= -0.166536E-08	= 0.250807E+06	= 0.250807E+04
0.14	= -0.174303E-04	= -0.174303E-08	= 0.262505E+06	= 0.262505E+04
0.15	= -0.181752E-04	= -0.181752E-08	= 0.273723E+06	= 0.273723E+04
0.16	= -0.188916E-04	= -0.188916E-08	= 0.284512E+06	= 0.284512E+04
0.17	= -0.195823E-04	= -0.195823E-08	= 0.294914E+06	= 0.294914E+04

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
0.18	-0.202499E-04	-0.202499E-08	0.304968E+06	0.304968E+04
0.19	-0.208964E-04	-0.208964E-08	0.314705E+06	0.314705E+04
0.20	-0.215236E-04	-0.215236E-08	0.324151E+06	0.324151E+04
0.21	-0.221332E-04	-0.221332E-08	0.333332E+06	0.333332E+04
0.22	-0.227265E-04	-0.227265E-08	0.342267E+06	0.342267E+04
0.23	-0.233048E-04	-0.233048E-08	0.350976E+06	0.350976E+04
0.24	-0.238691E-04	-0.238691E-08	0.359474E+06	0.359474E+04
0.25	-0.244204E-04	-0.244204E-08	0.367777E+06	0.367777E+04
0.26	-0.249595E-04	-0.249595E-08	0.375896E+06	0.375896E+04
0.27	-0.254872E-04	-0.254872E-08	0.383844E+06	0.383844E+04
0.28	-0.260042E-04	-0.260042E-08	0.391630E+06	0.391630E+04
0.29	-0.265112E-04	-0.265112E-08	0.399265E+06	0.399265E+04
0.30	-0.270086E-04	-0.270086E-08	0.406756E+06	0.406756E+04
0.31	-0.274971E-04	-0.274971E-08	0.414112E+06	0.414112E+04
0.32	-0.279770E-04	-0.279770E-08	0.421340E+06	0.421340E+04
0.33	-0.284488E-04	-0.284488E-08	0.428446E+06	0.428446E+04
0.34	-0.289129E-04	-0.289129E-08	0.435435E+06	0.435435E+04
0.35	-0.293697E-04	-0.293697E-08	0.442315E+06	0.442315E+04
0.36	-0.298195E-04	-0.298195E-08	0.449089E+06	0.449089E+04
0.37	-0.302626E-04	-0.302626E-08	0.455762E+06	0.455762E+04
0.38	-0.306993E-04	-0.306993E-08	0.462339E+06	0.462339E+04
0.39	-0.311299E-04	-0.311299E-08	0.468824E+06	0.468824E+04
0.40	-0.315546E-04	-0.315546E-08	0.475220E+06	0.475220E+04
0.41	-0.319737E-04	-0.319737E-08	0.481531E+06	0.481531E+04
0.42	-0.323873E-04	-0.323873E-08	0.487761E+06	0.487761E+04
0.43	-0.327958E-04	-0.327958E-08	0.493912E+06	0.493912E+04
0.44	-0.331992E-04	-0.331992E-08	0.499988E+06	0.499988E+04
0.45	-0.335977E-04	-0.335977E-08	0.505990E+06	0.505990E+04
0.46	-0.339916E-04	-0.339916E-08	0.511922E+06	0.511922E+04
0.47	-0.343810E-04	-0.343810E-08	0.517786E+06	0.517786E+04
0.48	-0.347660E-04	-0.347660E-08	0.523585E+06	0.523585E+04

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
0.49	= −0.351468E−04	= −0.351468E−08	= 0.529320E+06	= 0.529320E+04
0.50	= −0.355235E−04	= −0.355235E−08	= 0.534993E+06	= 0.534993E+04
0.51	= −0.358963E−04	= −0.358963E−08	= 0.540607E+06	= 0.540607E+04
0.52	= −0.362652E−04	= −0.362652E−08	= 0.546163E+06	= 0.546163E+04
0.53	= −0.366305E−04	= −0.366305E−08	= 0.551663E+06	= 0.551664E+04
0.54	= −0.369921E−04	= −0.369921E−08	= 0.557110E+06	= 0.557110E+04
0.55	= −0.373502E−04	= −0.373502E−08	= 0.562503E+06	= 0.562503E+04
0.56	= −0.377049E−04	= −0.377049E−08	= 0.567845E+06	= 0.567845E+04
0.57	= −0.380563E−04	= −0.380563E−08	= 0.573137E+06	= 0.573137E+04
0.58	= −0.384045E−04	= −0.384045E−08	= 0.578381E+06	= 0.578381E+04
0.59	= −0.387495E−04	= −0.387495E−08	= 0.583578E+06	= 0.583573E+04
0.60	= −0.390916E−04	= −0.390916E−08	= 0.588729E+06	= 0.588729E+04
0.61	= −0.394306E−04	= −0.394306E−08	= 0.593835E+06	= 0.593835E+04
0.62	= −0.397668E−04	= −0.397668E−08	= 0.598897E+06	= 0.598897E+04
0.63	= −0.401001E−04	= −0.401001E−08	= 0.603918E+06	= 0.603918E+04
0.64	= −0.404307E−04	= −0.404307E−08	= 0.608896E+06	= 0.608896E+04
0.65	= −0.407586E−04	= −0.407586E−08	= 0.613835E+06	= 0.613835E+04
0.66	= −0.410839E−04	= −0.410839E−08	= 0.618734E+06	= 0.618734E+04
0.67	= −0.414066E−04	= −0.414066E−08	= 0.623594E+06	= 0.623594E+04
0.68	= −0.417269E−04	= −0.417269E−08	= 0.628417E+06	= 0.628417E+04
0.69	= −0.420447E−04	= −0.420447E−08	= 0.633203E+06	= 0.633203E+04
0.70	= −0.423601E−04	= −0.423601E−08	= 0.637954E+06	= 0.637954E+04
0.71	= −0.426732E−04	= −0.426732E−08	= 0.642669E+06	= 0.642669E+04
0.72	= −0.429840E−04	= −0.429840E−08	= 0.647350E+06	= 0.647350E+04
0.73	= −0.432926E−04	= −0.432926E−08	= 0.651997E+06	= 0.651997E+04
0.74	= −0.435990E−04	= −0.435990E−08	= 0.656611E+06	= 0.656611E+04
0.75	= −0.439032E−04	= −0.439032E−08	= 0.661193E+06	= 0.661193E+04
0.76	= −0.442054E−04	= −0.442054E−08	= 0.665744E+06	= 0.665744E+04
0.77	= −0.445055E−04	= −0.445055E−08	= 0.670264E+06	= 0.670264E+04
0.78	= −0.448036E−04	= −0.448036E−08	= 0.674753E+06	= 0.674753E+04
0.79	= −0.450997E−04	= −0.450997E−08	= 0.679213E+06	= 0.679213E+04

V_s (volt)	Q_s (coul/m²)	Q_s (coul/cm²)	E_s (volt/m)	E_s (volt/cm)
= 0.80 =	−0.453939E−04 =	−0.453939E−08 =	0.6836444E+06 =	0.6836444E+04
= 0.81 =	−0.456862E−04 =	−0.456862E−08 =	0.6880945E+06 =	0.6880945E+04
= 0.82 =	−0.459767E−04 =	−0.459767E−08 =	0.6924920E+06 =	0.6924920E+04
= 0.83 =	−0.462653E−04 =	−0.462653E−08 =	0.6967766E+06 =	0.6967767E+04
= 0.84 =	−0.465521E−04 =	−0.465521E−08 =	0.7010866E+06 =	0.7010866E+04
= 0.85 =	−0.468372E−04 =	−0.468372E−08 =	0.7053809E+06 =	0.7053809E+04
= 0.86 =	−0.471205E−04 =	−0.471205E−08 =	0.7096647E+06 =	0.7096647E+04
= 0.87 =	−0.474022E−04 =	−0.474022E−08 =	0.7138889E+06 =	0.7138889E+04
= 0.88 =	−0.476822E−04 =	−0.476822E−08 =	0.7181105E+06 =	0.7181106E+04
= 0.89 =	−0.479605E−04 =	−0.479605E−08 =	0.7222298E+06 =	0.7222298E+04
= 0.90 =	−0.482373E−04 =	−0.482373E−08 =	0.7264466E+06 =	0.7264466E+04
= 0.91 =	−0.485125E−04 =	−0.485125E−08 =	0.7306619E+06 =	0.7306619E+04
= 0.92 =	−0.487861E−04 =	−0.487861E−08 =	0.7347319E+06 =	0.7347319E+04
= 0.93 =	−0.490582E−04 =	−0.490582E−08 =	0.7388288E+06 =	0.7388288E+04
= 0.94 =	−0.493288E−04 =	−0.493288E−08 =	0.7429063E+06 =	0.7429063E+04
= 0.95 =	−0.495979E−04 =	−0.495979E−08 =	0.7469957E+06 =	0.7469957E+04
= 0.96 =	−0.498656E−04 =	−0.498656E−08 =	0.7509882E+06 =	0.7509882E+04
= 0.97 =	−0.501318E−04 =	−0.501318E−08 =	0.7549997E+06 =	0.7549997E+04
= 0.98 =	−0.503966E−04 =	−0.503966E−08 =	0.7589365E+06 =	0.7589366E+04
= 0.99 =	−0.506601E−04 =	−0.506601E−08 =	0.7629953E+06 =	0.7629953E+04
= 1.00 =	−0.509222E−04 =	−0.509222E−08 =	0.7669000E+06 =	0.7669000E+04
= 1.01 =	−0.511829E−04 =	−0.511829E−08 =	0.7708327E+06 =	0.7708327E+04
= 1.02 =	−0.514424E−04 =	−0.514424E−08 =	0.7747735E+06 =	0.7747735E+04
= 1.03 =	−0.517005E−04 =	−0.517005E−08 =	0.7786822E+06 =	0.7786822E+04
= 1.04 =	−0.519574E−04 =	−0.519574E−08 =	0.7824911E+06 =	0.7824911E+04
= 1.05 =	−0.522130E−04 =	−0.522130E−08 =	0.7863400E+06 =	0.7863400E+04
= 1.06 =	−0.524674E−04 =	−0.524674E−08 =	0.7901171E+06 =	0.7901171E+04
= 1.07 =	−0.527205E−04 =	−0.527205E−08 =	0.7939844E+06 =	0.7939844E+04
= 1.08 =	−0.529726E−04 =	−0.529726E−08 =	0.7977805E+06 =	0.7977805E+04
= 1.09 =	−0.532235E−04 =	−0.532235E−08 =	0.8015588E+06 =	0.8015588E+04
= 1.10 =	−0.534733E−04 =	−0.534733E−08 =	0.8053321E+06 =	0.8053321E+04

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
1.11	= −0.537221E−04	= −0.537221E−08	= 0.809067E+06	= 0.809067E+04
1.12	= −0.539699E−04	= −0.539699E−08	= 0.812800E+06	= 0.812800E+04
1.13	= −0.542169E−04	= −0.542169E−08	= 0.816519E+06	= 0.816519E+04
1.14	= −0.544631E−04	= −0.544631E−08	= 0.820228E+06	= 0.820228E+04
1.15	= −0.547089E−04	= −0.547089E−08	= 0.823930E+06	= 0.823930E+04
1.16	= −0.549545E−04	= −0.549545E−08	= 0.827629E+05	= 0.827629E+04
1.17	= −0.552004E−04	= −0.552004E−08	= 0.831331E+06	= 0.831331E+04
1.18	= −0.554470E−04	= −0.554470E−08	= 0.835045E+06	= 0.835045E+04
1.19	= −0.556954E−04	= −0.556954E−08	= 0.838786E+06	= 0.838786E+04
1.20	= −0.559467E−04	= −0.559467E−08	= 0.842571E+06	= 0.842571E+04
1.21	= −0.562030E−04	= −0.562030E−08	= 0.846431E+06	= 0.846431E+04
1.22	= −0.564669E−04	= −0.564669E−08	= 0.850406E+06	= 0.850406E+04
1.23	= −0.567424E−04	= −0.567424E−08	= 0.854555E+06	= 0.854555E+04
1.24	= −0.570354E−04	= −0.570354E−08	= 0.858967E+06	= 0.858967E+04
1.25	= −0.573544E−04	= −0.573544E−08	= 0.863771E+06	= 0.863771E+04
1.26	= −0.577117E−04	= −0.577117E−08	= 0.869152E+06	= 0.869152E+04
1.27	= −0.581252E−04	= −0.581252E−08	= 0.875380E+06	= 0.875380E+04
1.28	= −0.586210E−04	= −0.586210E−08	= 0.882847E+06	= 0.882847E+04
1.29	= −0.592366E−04	= −0.592366E−08	= 0.892118E+06	= 0.892118E+04
1.30	= −0.600255E−04	= −0.600255E−08	= 0.903999E+06	= 0.903999E+04
1.31	= −0.610639E−04	= −0.610639E−08	= 0.919637E+06	= 0.919637E+04
1.32	= −0.624581E−04	= −0.624581E−08	= 0.940635E+06	= 0.940635E+04
1.33	= −0.643547E−04	= −0.643547E−08	= 0.969197E+06	= 0.969198E+04
1.34	= −0.669504E−04	= −0.669504E−08	= 0.100829E+07	= 0.100829E+05
1.35	= −0.705021E−04	= −0.705021E−08	= 0.106178E+07	= 0.106178E+05
1.36	= −0.753342E−04	= −0.753342E−08	= 0.113455E+07	= 0.113455E+05
1.37	= −0.818410E−04	= −0.818410E−08	= 0.123255E+07	= 0.123255E+05
1.38	= −0.904870E−04	= −0.904870E−08	= 0.136276E+07	= 0.136276E+05
1.39	= −0.101804E−03	= −0.101804E−07	= 0.153320E+07	= 0.153329E+05
1.40	= −0.116398E−03	= −0.116398E−07	= 0.175299E+07	= 0.175299E+05
1.41	= −0.134960E−03	= −0.134960E−07	= 0.203253E+07	= 0.203253E+05

V_s (volt)		Q_s (coul/m^2)		Q_s (coul/cm^2)		E_s (volt/m)		E_s (volt/cm)
1.42	=	-0.158289E-03	=	-0.158289E-07	=	0.238388E+07	=	0.238388E+05
1.43	=	-0.187331E-03	=	-0.187331E-07	=	0.282126E+07	=	0.282126E+05
1.44	=	-0.223217E-03	=	-0.223217E-07	=	0.336171E+07	=	0.336171E+05
1.45	=	-0.267315E-03	=	-0.267315E-07	=	0.402582E+07	=	0.402582E+05
1.46	=	-0.321279E-03	=	-0.321279E-07	=	0.483855E+07	=	0.483855E+05
1.47	=	-0.387129E-03	=	-0.387129E-07	=	0.583026E+07	=	0.583026E+05
1.48	=	-0.467316E-03	=	-0.467316E-07	=	0.703790E+07	=	0.703790E+05
1.49	=	-0.564824E-03	=	-0.564824E-07	=	0.850639E+07	=	0.850639E+05
1.50	=	-0.683267E-03	=	-0.683267E-07	=	0.102902E+08	=	0.102902E+06
1.51	=	-0.827046E-03	=	-0.827046E-07	=	0.124555E+08	=	0.124555E+06
1.52	=	-0.100149E-02	=	-0.100149E-06	=	0.150828E+08	=	0.150828E+06
1.53	=	-0.121309E-02	=	-0.121309E-06	=	0.182695E+08	=	0.182695E+06
1.54	=	-0.146968E-02	=	-0.146968E-06	=	0.221337E+08	=	0.221337E+06
1.55	=	-0.178078E-02	=	-0.178078E-06	=	0.268190E+08	=	0.268190E+06
1.56	=	-0.215793E-02	=	-0.215793E-06	=	0.324989E+08	=	0.324989E+06
1.57	=	-0.261512E-02	=	-0.261512E-06	=	0.393843E+08	=	0.393843E+06
1.58	=	-0.316932E-02	=	-0.316932E-06	=	0.477308E+08	=	0.477308E+06
1.59	=	-0.384107E-02	=	-0.384107E-06	=	0.578475E+08	=	0.578475E+06
1.60	=	-0.465530E-02	=	-0.465530E-06	=	0.701099E+08	=	0.701099E+06
1.61	=	-0.564219E-02	=	-0.564219E-06	=	0.849728E+08	=	0.849728E+06
1.62	=	-0.683841E-02	=	-0.683841E-06	=	0.102988E+09	=	0.102988E+07
1.63	=	-0.828826E-02	=	-0.828825E-06	=	0.124823E+09	=	0.124823E+07
1.64	=	-0.100455E-01	=	-0.100455E-05	=	0.151238E+09	=	0.151238E+07
1.65	=	-0.121754E-01	=	-0.121754E-05	=	0.183365E+09	=	0.183365E+07
1.66	=	-0.147570E-01	=	-0.147570E-05	=	0.222244E+09	=	0.222244E+07
1.67	=	-0.178859E-01	=	-0.178859E-05	=	0.269366E+09	=	0.269366E+07
1.68	=	-0.216783E-01	=	-0.216783E-05	=	0.326486E+09	=	0.326486E+07
1.69	=	-0.262747E-01	=	-0.262747E-05	=	0.395703E+09	=	0.395703E+07
1.70	=	-0.318459E-01	=	-0.318459E-05	=	0.479607E+09	=	0.479607E+07
1.71	=	-0.385982E-01	=	-0.385982E-05	=	0.581299E+09	=	0.581299E+07
1.72	=	-0.467823E-01	=	-0.467823E-05	=	0.704552E+09	=	0.704552E+07
1.73	=	-0.567016E-01	=	-0.567016E-05	=	0.853939E+09	=	0.853949E+07
1.74	=	-0.687248E-01	=	-0.687248E-05	=	0.103501E+10	=	0.103501E+08
1.75	=	-0.832967E-01	=	-0.832967E-05	=	0.125447E+10	=	0.125447E+08

Table 3.   Relation between Q_S, E_S and V_S.

```
C-FOCAL,1969

01.01 FOR V=-1.50,0.05,-0.05; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=6.64E-11
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET Q=A*FSQT(D+5.9E-22*G)
02.07 SET X=Q/B
02.08 TYPE %3.02,V," ", %,0," ", %,0*1E-4," ", %,-V," ", %,-X*1E-2,!
*GO
```

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
=-1.50	= 0.280121E+08	= 0.280121E+04	=-0.421869E+18	=-0.421869E+16
=-1.45	= 0.107096E+08	= 0.107096E+04	=-0.151289E+18	=-0.161289E+16
=-1.40	= 0.409448E+07	= 0.409448E+03	=-0.616638E+17	=-0.616638E+15
=-1.35	= 0.156539E+07	= 0.156539E+03	=-0.235752E+17	=-0.235752E+15
=-1.30	= 0.598482E+06	= 0.598482E+02	=-0.901328E+16	=-0.901328E+14
=-1.25	= 0.228812E+06	= 0.228812E+02	=-0.344596E+16	=-0.344596E+14
=-1.20	= 0.874790E+05	= 0.874799E+01	=-0.131745E+16	=-0.131745E+14
=-1.15	= 0.334450E+05	= 0.334450E+01	=-0.503689E+15	=-0.503689E+13
=-1.10	= 0.127866E+05	= 0.127866E+01	=-0.192570E+15	=-0.192570E+13
=-1.05	= 0.488858E+04	= 0.488858E+00	=-0.736231E+14	=-0.736231E+12
=-1.00	= 0.186900E+04	= 0.186900E+00	=-0.281476E+14	=-0.281476E+12
=-0.95	= 0.714556E+03	= 0.714556E-01	=-0.107614E+14	=-0.107614E+12
=-0.90	= 0.273188E+03	= 0.273188E-01	=-0.411427E+13	=-0.411427E+11
=-0.85	= 0.104445E+03	= 0.104445E-01	=-0.157297E+13	=-0.157297E+11

V_s (volt)		Q_s (coul/m^2)		Q_s (coul/cm^2)		E_s (volt/m)		E_s (volt/cm)
=-0.80	=	0.399313E+02	=	0.399313E-02	=-0.601376E+12	=-0.601376E+10
=-0.75	=	0.152665E+02	=	0.152665E-02	=-0.229918E+12	=-0.229918E+10
=-0.70	=	0.583669E+01	=	0.583669E-03	=-0.879019E+11	=-0.879020E+09
=-0.65	=	0.223148E+01	=	0.223148E-03	=-0.336066E+11	=-0.336066E+09
=-0.60	=	0.853138E+00	=	0.853138E-04	=-0.128485E+11	=-0.128485E+09
=-0.55	=	0.326172E+00	=	0.326172E-04	=-0.491223E+10	=-0.491223E+08
=-0.50	=	0.124702E+00	=	0.124702E-04	=-0.187804E+10	=-0.187804E+08
=-0.45	=	0.476759E-01	=	0.476759E-05	=-0.718010E+09	=-0.718010E+07
=-0.40	=	0.182274E-01	=	0.182274E-05	=-0.274509E+09	=-0.274509E+07
=-0.35	=	0.696861E-02	=	0.696861E-06	=-0.104949E+09	=-0.104949E+07
=-0.30	=	0.266410E-02	=	0.266410E-06	=-0.401220E+08	=-0.401220E+06
=-0.25	=	0.101824E-02	=	0.101824E-06	=-0.153349E+08	=-0.153349E+06
=-0.20	=	0.388657E-03	=	0.388657E-07	=-0.585327E+07	=-0.585327E+05
=-0.15	=	0.147305E-03	=	0.147305E-07	=-0.221844E+07	=-0.221844E+05
=-0.10	=	0.538951E-04	=	0.538951E-08	=-0.811673E+06	=-0.811673E+04
=-0.05	=	0.164701E-04	=	0.164701E-08	=-0.248043E+06	=-0.248043E+04

*

Table 4. Relation between Q_s, E_s and V_s.

```
C-FOCAL,1969

01.01 FOR V=-1.00,0.01,-0.01; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=6.64E-11
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET Q=A*FSQT(D+5.9E-22*G)
02.07 SET X=Q/B
02.08 TYPE %3.02,V," ",%3.0," ",%3.0*1E-4," ",%3.0," ",Z,-X," ",Z,-X*1E-2,!
*GO
```

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
= -1.00	= 0.186898E+04	= 0.186898E+00	= -0.281473E+14	= -0.281473E+12
= -0.99	= 0.154202E+04	= 0.154202E+00	= -0.232232E+14	= -0.232232E+12
= -0.98	= 0.127226E+04	= 0.127226E+00	= -0.191606E+14	= -0.191606E+12
= -0.97	= 0.104969E+04	= 0.104969E+00	= -0.158086E+14	= -0.158086E+12
= -0.96	= 0.866058E+03	= 0.866058E-01	= -0.130439E+14	= -0.130439E+12
= -0.95	= 0.714549E+03	= 0.714549E-01	= -0.107613E+14	= -0.107613E+12
= -0.94	= 0.589544E+03	= 0.589544E-01	= -0.887868E+13	= -0.887868E+11
= -0.93	= 0.486410E+03	= 0.486410E-01	= -0.732545E+13	= -0.732545E+11
= -0.92	= 0.401318E+03	= 0.401318E-01	= -0.604394E+13	= -0.604394E+11
= -0.91	= 0.331110E+03	= 0.331110E-01	= -0.498660E+13	= -0.498660E+11
= -0.90	= 0.273186E+03	= 0.273186E-01	= -0.411424E+13	= -0.411424E+11
= -0.89	= 0.225395E+03	= 0.225395E-01	= -0.339450E+13	= -0.339450E+11
= -0.88	= 0.185964E+03	= 0.185964E-01	= -0.280066E+13	= -0.280066E+11
= -0.87	= 0.153431E+03	= 0.153431E-01	= -0.231071E+13	= -0.231071E+11
= -0.86	= 0.126590E+03	= 0.126590E-01	= -0.190648E+13	= -0.190648E+11
= -0.85	= 0.104444E+03	= 0.104444E-01	= -0.157295E+13	= -0.157295E+11
= -0.84	= 0.861728E+02	= 0.861728E-02	= -0.129778E+13	= -0.129778E+11
= -0.83	= 0.710974E+02	= 0.710974E-02	= -0.107074E+13	= -0.107074E+11

V_s (volt)	Q_s (coul/m^2)	Q_s (coul/cm^2)	E_s (volt/m)	E_s (volt/cm)
=-0.82	= 0.586597E+02	= 0.586597E-02	=-0.883429E+12	=-0.883429E+10
=-0.81	= 0.483977E+02	= 0.483977E-02	=-0.723881E+12	=-0.723881E+10
=-0.80	= 0.399310E+02	= 0.399310E-02	=-0.601371E+12	=-0.601371E+10
=-0.79	= 0.329454E+02	= 0.329454E-02	=-0.496166E+12	=-0.496166E+10
=-0.78	= 0.271820E+02	= 0.271820E-02	=-0.409367E+12	=-0.409367E+10
=-0.77	= 0.224267E+02	= 0.224267E-02	=-0.337752E+12	=-0.337752E+10
=-0.76	= 0.185034E+02	= 0.185034E-02	=-0.278665E+12	=-0.278665E+10
=-0.75	= 0.152664E+02	= 0.152664E-02	=-0.229915E+12	=-0.229915E+10
=-0.74	= 0.125957E+02	= 0.125957E-02	=-0.189694E+12	=-0.189694E+10
=-0.73	= 0.103922E+02	= 0.103922E-02	=-0.155509E+12	=-0.155509E+10
=-0.72	= 0.857418E+01	= 0.857418E-03	=-0.129129E+12	=-0.129129E+10
=-0.71	= 0.707420E+01	= 0.707420E-03	=-0.106539E+12	=-0.106539E+10
=-0.70	= 0.583664E+01	= 0.583664E-03	=-0.879012E+11	=-0.879012E+09
=-0.69	= 0.481557E+01	= 0.481557E-03	=-0.725237E+11	=-0.725237E+09
=-0.68	= 0.397314E+01	= 0.397314E-03	=-0.598364E+11	=-0.598364E+09
=-0.67	= 0.327807E+01	= 0.327807E-03	=-0.493686E+11	=-0.493686E+09
=-0.66	= 0.270460E+01	= 0.270460E-03	=-0.407320E+11	=-0.407320E+09
=-0.65	= 0.223146E+01	= 0.223146E-03	=-0.336063E+11	=-0.336063E+09
=-0.64	= 0.184109E+01	= 0.184109E-03	=-0.277272E+11	=-0.277272E+09
=-0.63	= 0.151901E+01	= 0.151901E-03	=-0.228766E+11	=-0.228766E+09
=-0.62	= 0.125327E+01	= 0.125327E-03	=-0.188746E+11	=-0.188746E+09
=-0.61	= 0.103403E+01	= 0.103403E-03	=-0.155727E+11	=-0.155727E+09
=-0.60	= 0.853131E+00	= 0.853131E-04	=-0.128484E+11	=-0.128484E+09
=-0.59	= 0.703883E+00	= 0.703883E-04	=-0.106006E+11	=-0.106006E+09
=-0.58	= 0.580745E+00	= 0.580745E-04	=-0.874616E+10	=-0.874616E+08
=-0.57	= 0.479150E+00	= 0.479150E-04	=-0.721612E+10	=-0.721612E+08
=-0.56	= 0.395327E+00	= 0.395327E-04	=-0.595372E+10	=-0.595372E+08
=-0.55	= 0.326169E+00	= 0.326169E-04	=-0.491121E+10	=-0.491121E+08
=-0.54	= 0.269108E+00	= 0.269108E-04	=-0.405283E+10	=-0.405283E+08
=-0.53	= 0.222031E+00	= 0.222030E-04	=-0.334383E+10	=-0.334383E+08
=-0.52	= 0.183188E+00	= 0.183188E-04	=-0.275886E+10	=-0.275886E+08

V_s (volt)	Q_s (coul/m²)	Q_s (coul/cm²)	E_s (volt/m)	E_s (volt/cm)
-0.51	0.151141E+00	0.151141E-04	-0.227622E+10	-0.227622E+08
-0.50	0.124701E+00	0.124701E-04	-0.187892E+10	-0.187892E+08
-0.49	0.102885E+00	0.102885E-04	-0.154948E+10	-0.154948E+08
-0.48	0.848865E-01	0.848865E-05	-0.127841E+10	-0.127841E+08
-0.47	0.700365E-01	0.700365E-05	-0.105477E+10	-0.105477E+08
-0.46	0.577842E-01	0.577842E-05	-0.870244E+09	-0.870244E+07
-0.45	0.476754E-01	0.476754E-05	-0.718003E+09	-0.718003E+07
-0.44	0.393350E-01	0.393350E-05	-0.592395E+09	-0.592395E+07
-0.43	0.324538E-01	0.324538E-05	-0.488762E+09	-0.488762E+07
-0.42	0.267763E-01	0.267763E-05	-0.403257E+09	-0.403257E+07
-0.41	0.220920E-01	0.220920E-05	-0.332711E+09	-0.332711E+07
-0.40	0.182272E-01	0.182272E-05	-0.274506E+09	-0.274506E+07
-0.39	0.150385E-01	0.150385E-05	-0.226483E+09	-0.226483E+07
-0.38	0.124077E-01	0.124077E-05	-0.186862E+09	-0.186862E+07
-0.37	0.102370E-01	0.102370E-05	-0.154172E+09	-0.154172E+07
-0.36	0.844615E-02	0.844615E-06	-0.127201E+09	-0.127201E+07
-0.35	0.696855E-02	0.696855E-06	-0.104948E+09	-0.104948E+07
-0.34	0.574945E-02	0.574945E-06	-0.865881E+08	-0.865881E+06
-0.33	0.474361E-02	0.474361E-06	-0.714399E+08	-0.714399E+06
-0.32	0.391372E-02	0.391372E-06	-0.589416E+08	-0.589416E+06
-0.31	0.322901E-02	0.322901E-06	-0.486297E+08	-0.486297E+06
-0.30	0.266408E-02	0.266408E-06	-0.401217E+08	-0.401217E+06
-0.29	0.219797E-02	0.219797E-06	-0.331019E+08	-0.331019E+06
-0.28	0.181339E-02	0.181339E-06	-0.273100E+08	-0.273100E+06
-0.27	0.149607E-02	0.149607E-06	-0.225312E+08	-0.225312E+06
-0.26	0.123426E-02	0.123426E-06	-0.185882E+08	-0.185882E+06
-0.25	0.101823E-02	0.101823E-06	-0.153348E+08	-0.153348E+06
-0.24	0.839977E-03	0.839977E-07	-0.126503E+08	-0.126503E+06
-0.23	0.692886E-03	0.692886E-07	-0.104350E+08	-0.104350E+06
-0.22	0.571506E-03	0.571506E-07	-0.860701E+07	-0.860701E+05
-0.21	0.471332E-03	0.471332E-07	-0.709838E+07	-0.709838E+05

V_s (volt)	Q_s (coul/m²)	Q_s (coul/cm²)	E_s (volt/m)	E_s (volt/cm)
= -0.20 =	0.388654E-03 =	0.388654E-07 =	-0.585322E+07 =	-0.585322E+05
= -0.19 =	0.320404E-03 =	0.320404E-07 =	-0.482537E+07 =	-0.482537E+05
= -0.18 =	0.264056E-03 =	0.264056E-07 =	-0.397674E+07 =	-0.397674E+05
= -0.17 =	0.217520E-03 =	0.217520E-07 =	-0.327591E+07 =	-0.327591E+05
= -0.16 =	0.179077E-03 =	0.179077E-07 =	-0.269694E+07 =	-0.269694E+05
= -0.15 =	0.147303E-03 =	0.147303E-07 =	-0.221843E+07 =	-0.221843E+05
= -0.14 =	0.121027E-03 =	0.121027E-07 =	-0.182270E+07 =	-0.182270E+05
= -0.13 =	0.992797E-04 =	0.992797E-08 =	-0.149518E+07 =	-0.149518E+05
= -0.12 =	0.812621E-04 =	0.812621E-08 =	-0.122383E+07 =	-0.122383E+05
= -0.11 =	0.663151E-04 =	0.663151E-08 =	-0.998722E+06 =	-0.998722E+04
= -0.10 =	0.538947E-04 =	0.538947E-08 =	-0.811667E+06 =	-0.811667E+04
= -0.09 =	0.435520E-04 =	0.435520E-08 =	-0.655903E+06 =	-0.655903E+04
= -0.08 =	0.349170E-04 =	0.349170E-08 =	-0.525858E+06 =	-0.525858E+04
= -0.07 =	0.276850E-04 =	0.276850E-08 =	-0.416942E+06 =	-0.416942E+04
= -0.06 =	0.216047E-04 =	0.216047E-08 =	-0.325373E+06 =	-0.325373E+04
= -0.05 =	0.164699E-04 =	0.164699E-08 =	-0.248041E+06 =	-0.248041E+04
= -0.04 =	0.121108E-04 =	0.121108E-08 =	-0.182392E+06 =	-0.182392E+04
= -0.03 =	0.838832E-05 =	0.838832E-09 =	-0.126330E+06 =	-0.126330E+04
= -0.02 =	0.518836E-05 =	0.518836E-09 =	-0.781380E+05 =	-0.781380E+03
= -0.01 =	0.241771E-05 =	0.241771E-09 =	-0.364113E+05 =	-0.364113E+03

*

3.2 <u>Theoretical Calculation of the Surface Conductance,</u>

  <u>$\Delta\sigma$, as the Function of the Surface Potential, V_s</u>.

From equation (68), the theoretical calculations
of surface conductance, $\Delta\sigma$, as a function of surface po-
tential V_s were made by numerical integration with small
intervals and the results are given in Figures 13, 14 and
15.

The values of parameters of Cu_2O in our calcula-
tions are the same as given in section 3.1, with

$$b = \frac{\mu_n}{\mu_p} \simeq 1,$$

$$\mu_p = 1.5 \times 10^{-2} \ m^2/V\text{-sec} = 150 \ cm^2/V\text{-sec.}[28]$$

The calculations are also made by using the PDP-
8E computer and the numerical results are shown in the
Tables 5 and 6.
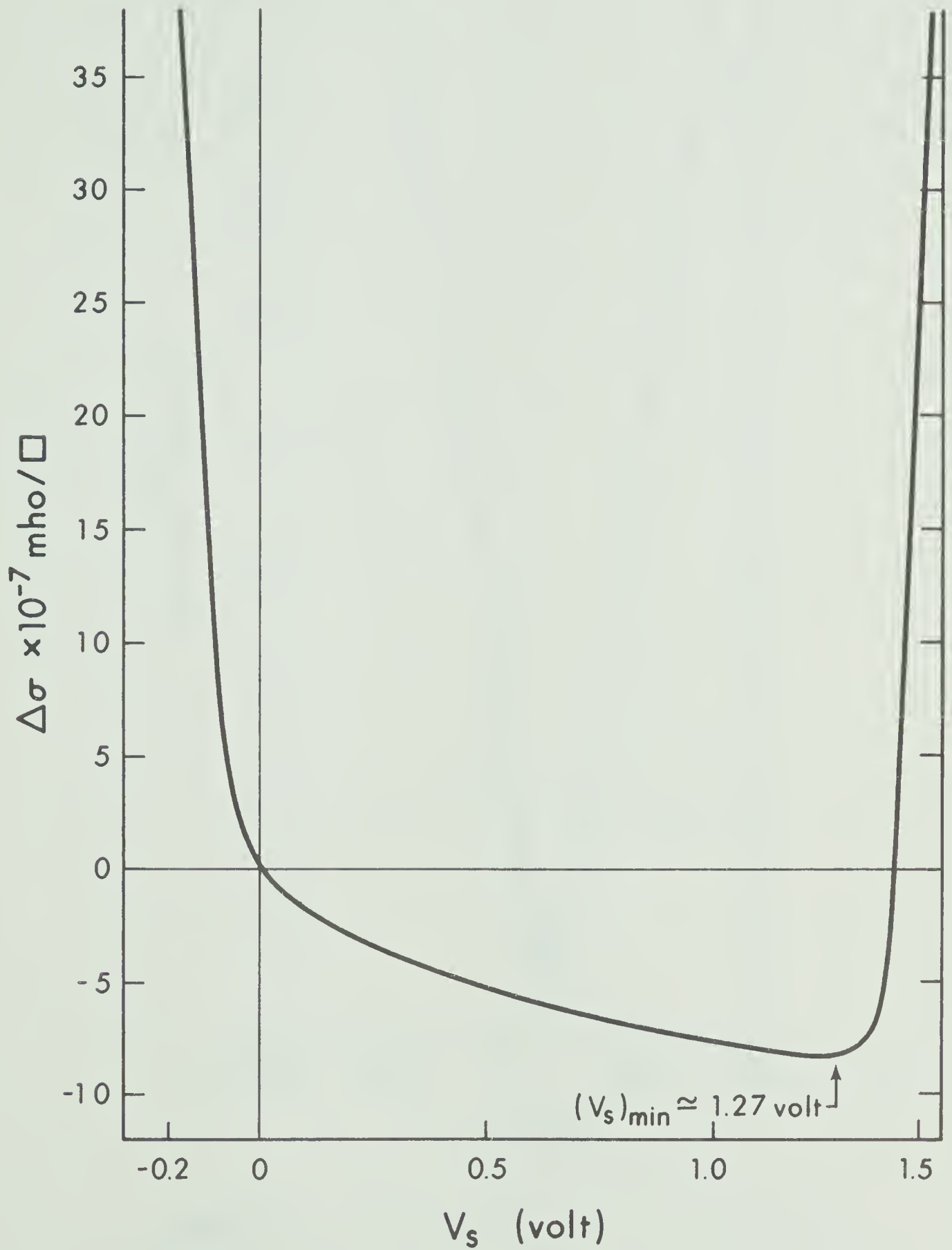
Figure 13. Theoretical curve of $\Delta\sigma$ vs V_s.
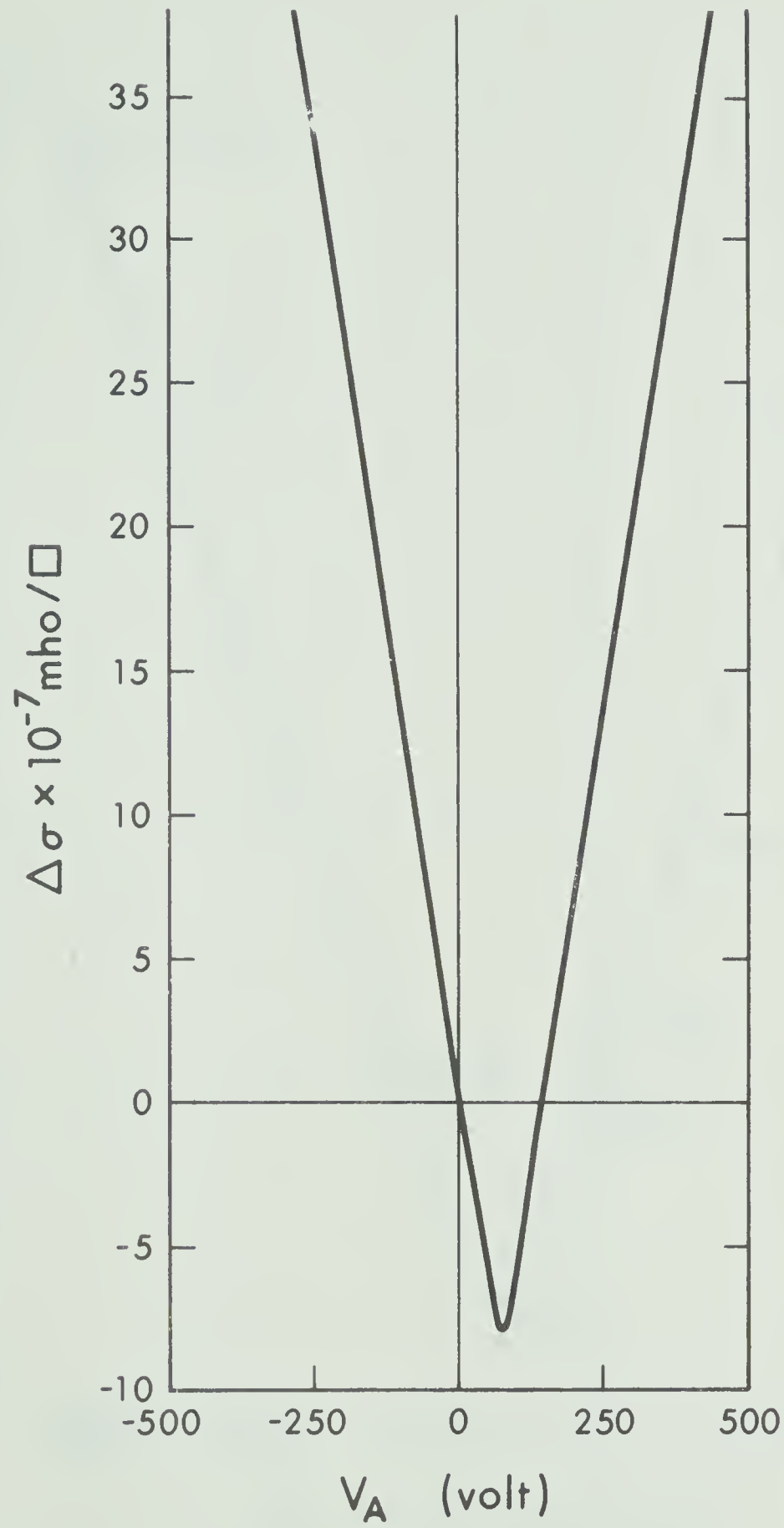
Figure 14. Theoretical curve of $\Delta\sigma$ vs V_A.
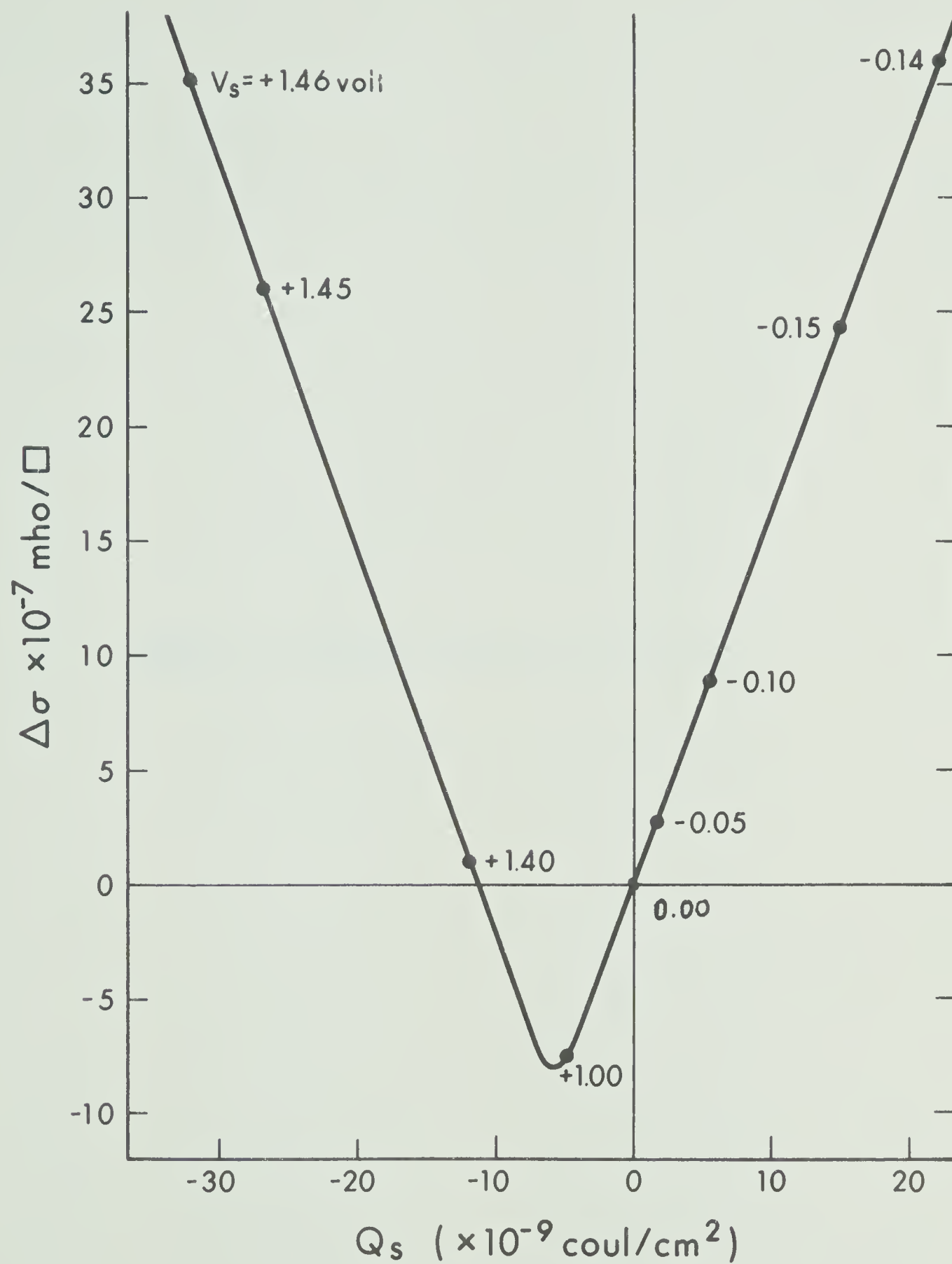
Figure 15. Theoretical curve of $\Delta\sigma$ vs Q_s.

Table 5. Relation between $\Delta\sigma$ and V_s.

C-FOCAL,1969

```
01.01 SET S=0.00
01.02 FOR I=0.01,0.01,2.00; DO 02.00
01.03 QUIT

02.01 SET A=38.46*I
02.02 SET B=FEXP(A)
02.03 SET C=(1/B-1+5.9E-22*(B-1))/FSQT(1/B+A-1+5.9E-22*(B-A-1))
02.04 SET Y=2.4E-6*0.01*C; SET S=S+Y
02.05 TYPE % 3.02,I,"          ", %,S,"          ", %,S*1E7,!
*GO
```

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ (x 10^{-7} mho/□)
= 0.01	=-0.299811E-07	=-0.299811E+00
= 0.02	=-0.566857E-07	=-0.566857E+00
= 0.03	=-0.806701E-07	=-0.806702E+00
= 0.04	=-0.102387E-06	=-0.102387E+01
= 0.05	=-0.122205E-06	=-0.122205E+01
= 0.06	=-0.140425E-06	=-0.140425E+01
= 0.07	=-0.157290E-06	=-0.157290E+01
= 0.08	=-0.173003E-06	=-0.173003E+01
= 0.09	=-0.187727E-06	=-0.187727E+01
= 0.10	=-0.201597E-06	=-0.201597E+01
= 0.11	=-0.214726E-06	=-0.214726E+01
= 0.12	=-0.227206E-06	=-0.227207E+01
= 0.13	=-0.239116E-06	=-0.239116E+01
= 0.14	=-0.250519E-06	=-0.250519E+01
= 0.15	=-0.261471E-06	=-0.261472E+01
= 0.16	=-0.272019E-06	=-0.272019E+01
= 0.17	=-0.282201E-06	=-0.282201E+01
= 0.18	=-0.292052E-06	=-0.292052E+01
= 0.19	=-0.301602E-06	=-0.301602E+01
= 0.20	=-0.310875E-06	=-0.310875E+01
= 0.21	=-0.319893E-06	=-0.319894E+01
= 0.22	=-0.328678E-06	=-0.328678E+01
= 0.23	=-0.337245E-06	=-0.337245E+01
= 0.24	=-0.345610E-06	=-0.345610E+01
= 0.25	=-0.353786E-06	=-0.353786E+01
= 0.26	=-0.361786E-06	=-0.361786E+01
= 0.27	=-0.369620E-06	=-0.369620E+01
= 0.28	=-0.377299E-06	=-0.377299E+01
= 0.29	=-0.384830E-06	=-0.384831E+01
= 0.30	=-0.392224E-06	=-0.392224E+01
= 0.31	=-0.399485E-06	=-0.399486E+01
= 0.32	=-0.406623E-06	=-0.406623E+01
= 0.33	=-0.413642E-06	=-0.413642E+01
= 0.34	=-0.420548E-06	=-0.420548E+01
= 0.35	=-0.427347E-06	=-0.427347E+01
= 0.36	=-0.434043E-06	=-0.434043E+01
= 0.37	=-0.440641E-06	=-0.440642E+01
= 0.38	=-0.447146E-06	=-0.447146E+01

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
= 0.39	= -0.453560E-06	= -0.453561E+01
= 0.40	= -0.459888E-06	= -0.459889E+01
= 0.41	= -0.466133E-06	= -0.466134E+01
= 0.42	= -0.472299E-06	= -0.472299E+01
= 0.43	= -0.478388E-06	= -0.478388E+01
= 0.44	= -0.484402E-06	= -0.484402E+01
= 0.45	= -0.490345E-06	= -0.490346E+01
= 0.46	= -0.496220E-06	= -0.496220E+01
= 0.47	= -0.502028E-06	= -0.502028E+01
= 0.48	= -0.507771E-06	= -0.507772E+01
= 0.49	= -0.513453E-06	= -0.513453E+01
= 0.50	= -0.519074E-06	= -0.519074E+01
= 0.51	= -0.524637E-06	= -0.524637E+01
= 0.52	= -0.530143E-06	= -0.530143E+01
= 0.53	= -0.535594E-06	= -0.535594E+01
= 0.54	= -0.540992E-06	= -0.540992E+01
= 0.55	= -0.546338E-06	= -0.546339E+01
= 0.56	= -0.551634E-06	= -0.551635E+01
= 0.57	= -0.556881E-06	= -0.556882E+01
= 0.58	= -0.562081E-06	= -0.562081E+01
= 0.59	= -0.567234E-06	= -0.567234E+01
= 0.60	= -0.572342E-06	= -0.572342E+01
= 0.61	= -0.577406E-06	= -0.577406E+01
= 0.62	= -0.582428E-06	= -0.582428E+01
= 0.63	= -0.587407E-06	= -0.587407E+01
= 0.64	= -0.592346E-06	= -0.592346E+01
= 0.65	= -0.597245E-06	= -0.597245E+01
= 0.66	= -0.602105E-06	= -0.602106E+01
= 0.67	= -0.606928E-06	= -0.606928E+01
= 0.68	= -0.611713E-06	= -0.611714E+01
= 0.69	= -0.616463E-06	= -0.616463E+01
= 0.70	= -0.621176E-06	= -0.621177E+01
= 0.71	= -0.625856E-06	= -0.625856E+01
= 0.72	= -0.630501E-06	= -0.630502E+01
= 0.73	= -0.635114E-06	= -0.635114E+01
= 0.74	= -0.639693E-06	= -0.639694E+01
= 0.75	= -0.644242E-06	= -0.644242E+01
= 0.76	= -0.648759E-06	= -0.648759E+01
= 0.77	= -0.653246E-06	= -0.653246E+01
= 0.78	= -0.657702E-06	= -0.657703E+01
= 0.79	= -0.662130E-06	= -0.662130E+01
= 0.80	= -0.666529E-06	= -0.666529E+01
= 0.81	= -0.670900E-06	= -0.670900E+01
= 0.82	= -0.675243E-06	= -0.675243E+01
= 0.83	= -0.679559E-06	= -0.679559E+01
= 0.84	= -0.683848E-06	= -0.683849E+01
= 0.85	= -0.688112E-06	= -0.688112E+01
= 0.86	= -0.692349E-06	= -0.692350E+01
= 0.87	= -0.696562E-06	= -0.696562E+01

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
= 0.88	= -0.706750E-06	= -0.706750E+01
= 0.89	= -0.704913E-06	= -0.704913E+01
= 0.90	= -0.709452E-06	= -0.709453E+01
= 0.91	= -0.713169E-06	= -0.713169E+01
= 0.92	= -0.717262E-06	= -0.717262E+01
= 0.93	= -0.721332E-06	= -0.721332E+01
= 0.94	= -0.725380E-06	= -0.725380E+01
= 0.95	= -0.729406E-06	= -0.729406E+01
= 0.96	= -0.733417E-06	= -0.733411E+01
= 0.97	= -0.737393E-06	= -0.737394E+01
= 0.98	= -0.741356E-06	= -0.741356E+01
= 0.99	= -0.745297E-06	= -0.745298E+01
= 1.00	= -0.749219E-06	= -0.749219E+01
= 1.01	= -0.753120E-06	= -0.753120E+01
= 1.02	= -0.757001E-06	= -0.757001E+01
= 1.03	= -0.760863E-06	= -0.760863E+01
= 1.04	= -0.764706E-06	= -0.764706E+01
= 1.05	= -0.768529E-06	= -0.768530E+01
= 1.06	= -0.772334E-06	= -0.772334E+01
= 1.07	= -0.776120E-06	= -0.776120E+01
= 1.08	= -0.779847E-06	= -0.779847E+01
= 1.09	= -0.783635E-06	= -0.783636E+01
= 1.10	= -0.787364E-06	= -0.787365E+01
= 1.11	= -0.791074E-06	= -0.791074E+01
= 1.12	= -0.794763E-06	= -0.794763E+01
= 1.13	= -0.798489E-06	= -0.798439E+01
= 1.14	= -0.802072E-06	= -0.802072E+01
= 1.15	= -0.805687E-06	= -0.805638E+01
= 1.16	= -0.809270E-06	= -0.809270E+01
= 1.17	= -0.812813E-06	= -0.812813E+01
= 1.18	= -0.816305E-06	= -0.816306E+01
= 1.19	= -0.819731E-06	= -0.819732E+01
= 1.20	= -0.823068E-06	= -0.823068E+01
= 1.21	= -0.826280E-06	= -0.826281E+01
= 1.22	= -0.829319E-06	= -0.829319E+01
= 1.23	= -0.832110E-06	= -0.832111E+01
= 1.24	= -0.834548E-06	= -0.834548E+01
= 1.25	= -0.836476E-06	= -0.836476E+01
= 1.26	= -0.837668E-06	= -0.837668E+01
= 1.27	= -0.837795E-06	= -0.837796E+01
= 1.28	= -0.836383E-06	= -0.836384E+01
= 1.29	= -0.832750E-06	= -0.832750E+01
= 1.30	= -0.825921E-06	= -0.825922E+01
= 1.31	= -0.814527E-06	= -0.814527E+01
= 1.32	= -0.796663E-06	= -0.796663E+01
= 1.33	= -0.769738E-06	= -0.769739E+01
= 1.34	= -0.730320E-06	= -0.730320E+01
= 1.35	= -0.674092E-06	= -0.674092E+01
= 1.36	= -0.595332E-06	= -0.595332E+01

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
= 1.37	=-0.487808E-06	=-0.487808E+01
= 1.38	=-0.343909E-06	=-0.343910E+01
= 1.39	=-0.155099E-06	=-0.155099E+01
= 1.40	= 0.882964E-07	= 0.882964E+00
= 1.41	= 0.397370E-06	= 0.397370E+01
= 1.42	= 0.785080E-06	= 0.785081E+01
= 1.43	= 0.126684E-05	= 0.126684E+02
= 1.44	= 0.186119E-05	= 0.186119E+02
= 1.45	= 0.259063E-05	= 0.259063E+02
= 1.46	= 0.348250E-05	= 0.348250E+02
= 1.47	= 0.457006E-05	= 0.457006E+02
= 1.48	= 0.589376E-05	= 0.589377E+02
= 1.49	= 0.750281E-05	= 0.750281E+02
= 1.50	= 0.945691E-05	= 0.945691E+02
= 1.51	= 0.118286E-04	= 0.118286E+03
= 1.52	= 0.147059E-04	= 0.147059E+03
= 1.53	= 0.181955E-04	= 0.181955E+03
= 1.54	= 0.224269E-04	= 0.224269E+03
= 1.55	= 0.275571E-04	= 0.275571E+03
= 1.56	= 0.337763E-04	= 0.337763E+03
= 1.57	= 0.413153E-04	= 0.413153E+03
= 1.58	= 0.504538E-04	= 0.504538E+03
= 1.59	= 0.615306E-04	= 0.615306E+03
= 1.60	= 0.749567E-04	= 0.749567E+03
= 1.61	= 0.912301E-04	= 0.912301E+03
= 1.62	= 0.110954E-03	= 0.110954E+04
= 1.63	= 0.134861E-03	= 0.134861E+04
= 1.64	= 0.163838E-03	= 0.163838E+04
= 1.65	= 0.198958E-03	= 0.198958E+04
= 1.66	= 0.241525E-03	= 0.241525E+04
= 1.67	= 0.293119E-03	= 0.293119E+04
= 1.68	= 0.355651E-03	= 0.355651E+04
= 1.69	= 0.431443E-03	= 0.431443E+04
= 1.70	= 0.523306E-03	= 0.523306E+04
= 1.71	= 0.634647E-03	= 0.634647E+04
= 1.72	= 0.769595E-03	= 0.769595E+04
= 1.73	= 0.933157E-03	= 0.933157E+04
= 1.74	= 0.113140E-02	= 0.113140E+05
= 1.75	= 0.137168E-02	= 0.137168E+05
= 1.76	= 0.166291E-02	= 0.166291E+05
= 1.77	= 0.201588E-02	= 0.201588E+05
= 1.78	= 0.244370E-02	= 0.244370E+05
= 1.79	= 0.296222E-02	= 0.296222E+05
= 1.80	= 0.359069E-02	= 0.359070E+05
= 1.81	= 0.435242E-02	= 0.435242E+05
= 1.82	= 0.527567E-02	= 0.527567E+05
= 1.83	= 0.639468E-02	= 0.639468E+05
= 1.84	= 0.775095E-02	= 0.775095E+05
= 1.85	= 0.939479E-02	= 0.939479E+05

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ (x 10^{-7} mho/□)
= 1.86	= 0.113872E-01	= 0.113872E+06
= 1.87	= 0.138020E-01	= 0.138020E+06
= 1.88	= 0.167289E-01	= 0.167289E+06
= 1.89	= 0.202764E-01	= 0.202764E+06
= 1.90	= 0.245760E-01	= 0.245760E+06
= 1.91	= 0.297874E-01	= 0.297874E+06
= 1.92	= 0.361038E-01	= 0.361037E+06
= 1.93	= 0.437594E-01	= 0.437594E+06
= 1.94	= 0.530382E-01	= 0.530382E+06
= 1.95	= 0.642845E-01	= 0.642844E+06
= 1.96	= 0.779153E-01	= 0.779153E+06
= 1.97	= 0.944363E-01	= 0.944363E+06
= 1.98	= 0.114460E+00	= 0.114460E+07
= 1.99	= 0.138730E+00	= 0.138730E+07
= 2.00	= 0.168146E+00	= 0.168146E+07

*

Table 6. Relation between $\Delta\sigma$ and V_s.

C-FOCAL,1969

```
01.01 SET S=0.00
01.02 FOR I=0.01,0.01,1.00; DO 02.00
01.03 QUIT

02.01 SET A=-38.46*I
02.02 SET B=FEXP(A)
02.03 SET C=(1/B-1+5.9E-22*(B-1))/FSQT(1/B+A-1+5.9E-22*(B-A-1))
02.04 SET Y=2.4E-6*0.01*C; SET S=S+Y
02.05 TYPE % 3.02,-I,"        ", %,S,"        ", %,S*1E7,!
*GO
```

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
=-0.01	= 0.387408E-07	= 0.387408E+00
=-0.02	= 0.833115E-07	= 0.833115E+00
=-0.03	= 0.134974E-06	= 0.134974E+01
=-0.04	= 0.195274E-06	= 0.195274E+01
=-0.05	= 0.266097E-06	= 0.266097E+01
=-0.06	= 0.349745E-06	= 0.349745E+01
=-0.07	= 0.449022E-06	= 0.449022E+01
=-0.08	= 0.567338E-06	= 0.567338E+01
=-0.09	= 0.708836E-06	= 0.708836E+01
=-0.10	= 0.878548E-06	= 0.878549E+01
=-0.11	= 0.108258E-05	= 0.108258E+02
=-0.12	= 0.132832E-05	= 0.132832E+02
=-0.13	= 0.162476E-05	= 0.162476E+02
=-0.14	= 0.198275E-05	= 0.198275E+02
=-0.15	= 0.241548E-05	= 0.241548E+02
=-0.16	= 0.293890E-05	= 0.293890E+02
=-0.17	= 0.357235E-05	= 0.357235E+02
=-0.18	= 0.433927E-05	= 0.433927E+02
=-0.19	= 0.526805E-05	= 0.526805E+02
=-0.20	= 0.639310E-05	= 0.639310E+02
=-0.21	= 0.775611E-05	= 0.775611E+02
=-0.22	= 0.940761E-05	= 0.940761E+02
=-0.23	= 0.114088E-04	= 0.114088E+03
=-0.24	= 0.138340E-04	= 0.138340E+03
=-0.25	= 0.167730E-04	= 0.167730E+03
=-0.26	= 0.203349E-04	= 0.203349E+03
=-0.27	= 0.246518E-04	= 0.246518E+03
=-0.28	= 0.298839E-04	= 0.298839E+03
=-0.29	= 0.362250E-04	= 0.362250E+03
=-0.30	= 0.439105E-04	= 0.439105E+03
=-0.31	= 0.532256E-04	= 0.532256E+03
=-0.32	= 0.645156E-04	= 0.645156E+03
=-0.33	= 0.781994E-04	= 0.781994E+03
=-0.34	= 0.947845E-04	= 0.947845E+03
=-0.35	= 0.114886E-03	= 0.114886E+04
=-0.36	= 0.139250E-03	= 0.139250E+04
=-0.37	= 0.168780E-03	= 0.168780E+04
=-0.38	= 0.204570E-03	= 0.204570E+04

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
=-0.39	= 0.247950E-03	= 0.247950E+04
=-0.40	= 0.300528E-03	= 0.300528E+04
=-0.41	= 0.364254E-03	= 0.364254E+04
=-0.42	= 0.441491E-03	= 0.441491E+04
=-0.43	= 0.535106E-03	= 0.535106E+04
=-0.44	= 0.648579E-03	= 0.648571E+04
=-0.45	= 0.786093E-03	= 0.786093E+04
=-0.46	= 0.952775E-03	= 0.952775E+04
=-0.47	= 0.115480E-02	= 0.115480E+05
=-0.48	= 0.139966E-02	= 0.139966E+05
=-0.49	= 0.169644E-02	= 0.169644E+05
=-0.50	= 0.205614E-02	= 0.205615E+05
=-0.51	= 0.249212E-02	= 0.249212E+05
=-0.52	= 0.302054E-02	= 0.302054E+05
=-0.53	= 0.366100E-02	= 0.366100E+05
=-0.54	= 0.443726E-02	= 0.443726E+05
=-0.55	= 0.537811E-02	= 0.537811E+05
=-0.56	= 0.651845E-02	= 0.651845E+05
=-0.57	= 0.790058E-02	= 0.790059E+05
=-0.58	= 0.957578E-02	= 0.957578E+05
=-0.59	= 0.116062E-01	= 0.116062E+06
=-0.60	= 0.140671E-01	= 0.140671E+06
=-0.61	= 0.170498E-01	= 0.170498E+06
=-0.62	= 0.206649E-01	= 0.206649E+06
=-0.63	= 0.250466E-01	= 0.250466E+06
=-0.64	= 0.303573E-01	= 0.303573E+06
=-0.65	= 0.367940E-01	= 0.367941E+06
=-0.66	= 0.445956E-01	= 0.445956E+06
=-0.67	= 0.540514E-01	= 0.540514E+06
=-0.68	= 0.655121E-01	= 0.655121E+06
=-0.69	= 0.794029E-01	= 0.794029E+06
=-0.70	= 0.962391E-01	= 0.962391E+06
=-0.71	= 0.116645E+00	= 0.116645E+07
=-0.72	= 0.141378E+00	= 0.141378E+07
=-0.73	= 0.171355E+00	= 0.171355E+07
=-0.74	= 0.207687E+00	= 0.207687E+07
=-0.75	= 0.251724E+00	= 0.251724E+07
=-0.76	= 0.305098E+00	= 0.305098E+07
=-0.77	= 0.369789E+00	= 0.369789E+07
=-0.78	= 0.448197E+00	= 0.448197E+07
=-0.79	= 0.543230E+00	= 0.543230E+07
=-0.80	= 0.658414E+00	= 0.658414E+07
=-0.81	= 0.798020E+00	= 0.798020E+07
=-0.82	= 0.967227E+00	= 0.967227E+07
=-0.83	= 0.117231E+01	= 0.117231E+08
=-0.84	= 0.142088E+01	= 0.142088E+08
=-0.85	= 0.172216E+01	= 0.172216E+08
=-0.86	= 0.208731E+01	= 0.208731E+08
=-0.87	= 0.252989E+01	= 0.252989E+08

V_s (volt)	$\Delta\sigma$ (mho/□)	$\Delta\sigma$ ($\times 10^{-7}$ mho/□)
$=-0.88$	$= 0.306632E+01$	$= 0.306632E+08$
$=-0.89$	$= 0.371648E+01$	$= 0.371648E+08$
$=-0.90$	$= 0.450449E+01$	$= 0.450449E+08$
$=-0.91$	$= 0.545960E+01$	$= 0.545960E+08$
$=-0.92$	$= 0.661722E+01$	$= 0.661722E+08$
$=-0.93$	$= 0.802029E+01$	$= 0.802029E+08$
$=-0.94$	$= 0.972086E+01$	$= 0.972086E+08$
$=-0.95$	$= 0.117820E+02$	$= 0.117820E+09$
$=-0.96$	$= 0.142802E+02$	$= 0.142802E+09$
$=-0.97$	$= 0.173081E+02$	$= 0.173081E+09$
$=-0.98$	$= 0.209780E+02$	$= 0.209780E+09$
$=-0.99$	$= 0.254260E+02$	$= 0.254260E+09$
$=-1.00$	$= 0.308172E+02$	$= 0.308172E+09$

*

3.3 Determination of the Value of the Surface Potential, V_{sm}, which Gives the Minimum Value of Surface Conductance, $\Delta\sigma_{min}$

By differentiating equation (68), we obtain

$$\frac{d\Delta\sigma}{dV} = \left(\frac{q}{kT}\right)\left(\frac{\varepsilon_o\varepsilon_s kT}{2}P_o\right)^{\frac{1}{2}}\mu P\frac{\left[e^{-\beta V} - 1 + \left(\frac{n_o}{P_o}\right)b(e^{\beta V} - 1)\right]}{\left[e^{-\beta V} + \beta V - 1 + \frac{n_o}{P_o}(e^{\beta V} - \beta V - 1)\right]^{\frac{1}{2}}}$$

To determine V_{sm}, one sets $\frac{d\Delta\sigma}{dV} = 0$, and then solves for the value of V which now becomes V_{sm}. In practice, we calculate the values of $\frac{d\Delta\sigma}{dV}$ as the function of V and then plot $\frac{d\Delta\sigma}{dV}$ vs V, and from the graph we can find the value of V (V_{sm}) which gives $\frac{d\Delta\sigma}{dV} = 0$. The results are given in Figure 16 and in the Tables 7 and 8.
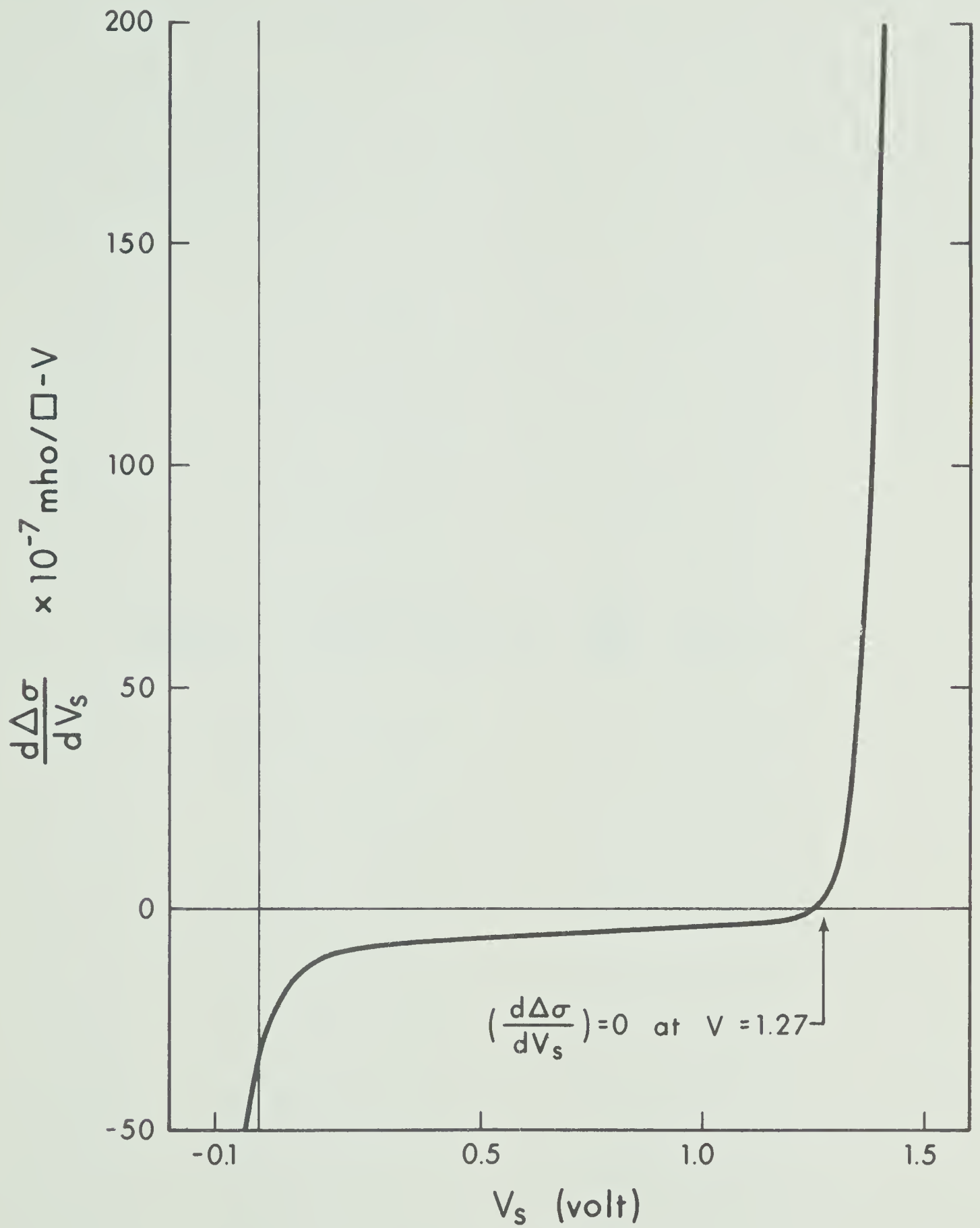
Figure 16. Theoretical curve of $\frac{d\Delta\sigma}{dV_s}$ vs V_s.

Table 7. Relation between $\dfrac{d\Delta\sigma}{dV_s}$ and V_s.

```
C-FOCAL,1969

01.01 FOR V=0.01,0.01,2.00; DO 02.00
01.02 QUIT

02.01 SET A=38.46*V
02.02 SET B=FEXP(A)
02.03 SET C=(1/B-1+5.9E-22*(B-1))/FSQT(1/B+A-1+5.9E-22*(B-A-1))
02.04 SET Y=2.4E-6*C
02.05 TYPE % 3.02,V,"          ", %,Y,"          ", %,Y*1E7,!
*GO
```

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ ($\times 10^{-7}$ mho/□-V)
= 0.01	=-0.299811E-05	=-0.299811E+02
= 0.02	=-0.267046E-05	=-0.267046E+02
= 0.03	=-0.239844E-05	=-0.239845E+02
= 0.04	=-0.217170E-05	=-0.217170E+02
= 0.05	=-0.198180E-05	=-0.198181E+02
= 0.06	=-0.182193E-05	=-0.182193E+02
= 0.07	=-0.168657E-05	=-0.168657E+02
= 0.08	=-0.157125E-05	=-0.157125E+02
= 0.09	=-0.147238E-05	=-0.147238E+02
= 0.10	=-0.138704E-05	=-0.138705E+02
= 0.11	=-0.131290E-05	=-0.131290E+02
= 0.12	=-0.124804E-05	=-0.124805E+02
= 0.13	=-0.119094E-05	=-0.119094E+02
= 0.14	=-0.114033E-05	=-0.114034E+02
= 0.15	=-0.109521E-05	=-0.109521E+02
= 0.16	=-0.105473E-05	=-0.105473E+02
= 0.17	=-0.101822E-05	=-0.101822E+02
= 0.18	=-0.985108E-06	=-0.985108E+01
= 0.19	=-0.954930E-06	=-0.954931E+01
= 0.20	=-0.927300E-06	=-0.927300E+01
= 0.21	=-0.901892E-06	=-0.901892E+01
= 0.22	=-0.878434E-06	=-0.878434E+01
= 0.23	=-0.856695E-06	=-0.856695E+01
= 0.24	=-0.836480E-06	=-0.836481E+01
= 0.25	=-0.817623E-06	=-0.817623E+01
= 0.26	=-0.799979E-06	=-0.799980E+01
= 0.27	=-0.783427E-06	=-0.783427E+01
= 0.28	=-0.767858E-06	=-0.767859E+01
= 0.29	=-0.753180E-06	=-0.753181E+01
= 0.30	=-0.739312E-06	=-0.739312E+01
= 0.31	=-0.726182E-06	=-0.726182E+01
= 0.32	=-0.713727E-06	=-0.713727E+01
= 0.33	=-0.701890E-06	=-0.701891E+01
= 0.34	=-0.690624E-06	=-0.690625E+01
= 0.35	=-0.679883E-06	=-0.679884E+01
= 0.36	=-0.669628E-06	=-0.669628E+01
= 0.37	=-0.659823E-06	=-0.659824E+01
= 0.38	=-0.650437E-06	=-0.650438E+01
= 0.39	=-0.641441E-06	=-0.641441E+01

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ (x 10^{-7} mho/□-V)
= 0.40	= -0.632807E-06	= -0.632807E+01
= 0.41	= -0.624513E-06	= -0.624513E+01
= 0.42	= -0.616537E-06	= -0.616537E+01
= 0.43	= -0.608859E-06	= -0.608859E+01
= 0.44	= -0.601460E-06	= -0.601461E+01
= 0.45	= -0.594325E-06	= -0.594326E+01
= 0.46	= -0.587438E-06	= -0.587439E+01
= 0.47	= -0.580785E-06	= -0.580786E+01
= 0.48	= -0.574353E-06	= -0.574354E+01
= 0.49	= -0.568131E-06	= -0.568131E+01
= 0.50	= -0.562106E-06	= -0.562106E+01
= 0.51	= -0.556269E-06	= -0.556269E+01
= 0.52	= -0.550609E-06	= -0.550610E+01
= 0.53	= -0.545120E-06	= -0.545120E+01
= 0.54	= -0.539791E-06	= -0.539791E+01
= 0.55	= -0.534616E-06	= -0.534616E+01
= 0.56	= -0.529586E-06	= -0.529586E+01
= 0.57	= -0.524696E-06	= -0.524696E+01
= 0.58	= -0.519939E-06	= -0.519939E+01
= 0.59	= -0.515309E-06	= -0.515309E+01
= 0.60	= -0.510800E-06	= -0.510801E+01
= 0.61	= -0.506408E-06	= -0.506408E+01
= 0.62	= -0.502127E-06	= -0.502128E+01
= 0.63	= -0.497953E-06	= -0.497954E+01
= 0.64	= -0.493882E-06	= -0.493882E+01
= 0.65	= -0.489908E-06	= -0.489909E+01
= 0.66	= -0.486029E-06	= -0.486030E+01
= 0.67	= -0.482241E-06	= -0.482241E+01
= 0.68	= -0.478540E-06	= -0.478540E+01
= 0.69	= -0.474922E-06	= -0.474923E+01
= 0.70	= -0.471386E-06	= -0.471387E+01
= 0.71	= -0.467928E-06	= -0.467928E+01
= 0.72	= -0.464544E-06	= -0.464545E+01
= 0.73	= -0.461233E-06	= -0.461234E+01
= 0.74	= -0.457992E-06	= -0.457992E+01
= 0.75	= -0.454818E-06	= -0.454818E+01
= 0.76	= -0.451709E-06	= -0.451709E+01
= 0.77	= -0.448663E-06	= -0.448663E+01
= 0.78	= -0.445678E-06	= -0.445678E+01
= 0.79	= -0.442752E-06	= -0.442752E+01
= 0.80	= -0.439882E-06	= -0.439882E+01
= 0.81	= -0.437068E-06	= -0.437068E+01
= 0.82	= -0.434307E-06	= -0.434307E+01
= 0.83	= -0.431597E-06	= -0.431598E+01
= 0.84	= -0.428938E-06	= -0.428938E+01
= 0.85	= -0.426327E-06	= -0.426328E+01
= 0.86	= -0.423764E-06	= -0.423764E+01
= 0.87	= -0.421246E-06	(= -0.421246E+01
= 0.88	= -0.418772E-06	= -0.418772E+01

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ ($\times 10^{-7}$ mho/□-V)
= 0.89	= -0.416342E-06	= -0.416342E+01
= 0.90	= -0.413953E-06	= -0.413953E+01
= 0.91	= -0.411605E-06	= -0.411605E+01
= 0.92	= -0.409296E-06	= -0.409296E+01
= 0.93	= -0.407026E-06	= -0.407026E+01
= 0.94	= -0.404793E-06	= -0.404793E+01
= 0.95	= -0.402596E-06	= -0.402596E+01
= 0.96	= -0.400434E-06	= -0.400434E+01
= 0.97	= -0.398306E-06	= -0.398306E+01
= 0.98	= -0.396211E-06	= -0.396211E+01
= 0.99	= -0.394148E-06	= -0.394148E+01
= 1.00	= -0.392116E-06	= -0.392116E+01
= 1.01	= -0.390113E-06	= -0.390113E+01
= 1.02	= -0.388137E-06	= -0.388138E+01
= 1.03	= -0.386188E-06	= -0.386188E+01
= 1.04	= -0.384262E-06	= -0.384262E+01
= 1.05	= -0.382356E-06	= -0.382356E+01
= 1.06	= -0.380465E-06	= -0.380465E+01
= 1.07	= -0.378585E-06	= -0.378585E+01
= 1.08	= -0.376706E-06	= -0.376706E+01
= 1.09	= -0.374817E-06	= -0.374817E+01
= 1.10	= -0.372900E-06	= -0.372900E+01
= 1.11	= -0.370930E-06	= -0.370930E+01
= 1.12	= -0.368871E-06	= -0.368871E+01
= 1.13	= -0.366671E-06	= -0.366672E+01
= 1.14	= -0.364254E-06	= -0.364254E+01
= 1.15	= -0.361506E-06	= -0.361507E+01
= 1.16	= -0.358266E-06	= -0.358266E+01
= 1.17	= -0.354295E-06	= -0.354295E+01
= 1.18	= -0.349244E-06	= -0.349244E+01
= 1.19	= -0.342604E-06	= -0.342604E+01
= 1.20	= -0.333633E-06	= -0.333633E+01
= 1.21	= -0.321243E-06	= -0.321243E+01
= 1.22	= -0.303851E-06	= -0.303851E+01
= 1.23	= -0.279144E-06	= -0.279145E+01
= 1.24	= -0.243759E-06	= -0.243759E+01
= 1.25	= -0.192804E-06	= -0.192804E+01
= 1.26	= -0.119201E-06	= -0.119201E+01
= 1.27	= -0.127377E-07	= -0.127377E+00
= 1.28	= 0.141208E-06	= 0.141208E+01
= 1.29	= 0.363391E-06	= 0.363391E+01
= 1.30	= 0.682837E-06	= 0.682837E+01
= 1.31	= 0.113942E-05	= 0.113942E+02
= 1.32	= 0.178641E-05	= 0.178641E+02
= 1.33	= 0.269249E-05	= 0.269249E+02
= 1.34	= 0.394187E-05	= 0.394187E+02
= 1.35	= 0.563181E-05	= 0.563181E+02
= 1.36	= 0.786698E-05	(× 10.786698E+02
= 1.37	= 0.107524E-04	= 0.107524E+03

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/$\square$-V)	$d\Delta\sigma/dV_s$ (x 10^{-7} mho/$\square$-V)
= 1.38	= 0.143899E-04	= 0.143899E+03
= 1.39	= 0.188811E-04	= 0.188811E+03
= 1.40	= 0.243395E-04	= 0.243395E+03
= 1.41	= 0.309074E-04	= 0.309074E+03
= 1.42	= 0.387710E-04	= 0.387710E+03
= 1.43	= 0.481756E-04	= 0.481756E+03
= 1.44	= 0.594354E-04	= 0.594354E+03
= 1.45	= 0.729443E-04	= 0.729443E+03
= 1.46	= 0.891869E-04	= 0.891869E+03
= 1.47	= 0.108756E-03	= 0.108756E+04
= 1.48	= 0.132371E-03	= 0.132371E+04
= 1.49	= 0.160904E-03	= 0.160904E+04
= 1.50	= 0.195410E-03	= 0.195411E+04
= 1.51	= 0.237169E-03	= 0.237169E+04
= 1.52	= 0.287727E-03	= 0.287727E+04
= 1.53	= 0.348962E-03	= 0.348962E+04
= 1.54	= 0.423141E-03	= 0.423141E+04
= 1.55	= 0.513019E-03	= 0.513019E+04
= 1.56	= 0.621925E-03	= 0.621925E+04
= 1.57	= 0.753900E-03	= 0.753900E+04
= 1.58	= 0.913845E-03	= 0.913846E+04
= 1.59	= 0.110768E-02	= 0.110768E+05
= 1.60	= 0.134261E-02	= 0.134261E+05
= 1.61	= 0.162734E-02	= 0.162734E+05
= 1.62	= 0.197244E-02	= 0.197244E+05
= 1.63	= 0.239069E-02	= 0.239069E+05
= 1.64	= 0.289763E-02	= 0.289763E+05
= 1.65	= 0.351204E-02	= 0.351204E+05
= 1.66	= 0.425674E-02	= 0.425675E+05
= 1.67	= 0.515933E-02	= 0.515933E+05
= 1.68	= 0.625328E-02	= 0.625328E+05
= 1.69	= 0.757919E-02	= 0.757919E+05
= 1.70	= 0.918628E-02	= 0.918628E+05
= 1.71	= 0.111341E-01	= 0.111341E+06
= 1.72	= 0.134949E-01	= 0.134949E+06
= 1.73	= 0.163562E-01	= 0.163562E+06
= 1.74	= 0.198245E-01	= 0.198245E+06
= 1.75	= 0.240279E-01	= 0.240279E+06
= 1.76	= 0.291225E-01	= 0.291225E+06
= 1.77	= 0.352975E-01	= 0.352975E+06
= 1.78	= 0.427817E-01	= 0.427817E+06
= 1.79	= 0.518527E-01	= 0.518527E+06
= 1.80	= 0.628472E-01	= 0.628472E+06
= 1.81	= 0.761728E-01	= 0.761728E+06
= 1.82	= 0.923249E-01	= 0.923248E+06
= 1.83	= 0.111901E+00	= 0.111901E+07
= 1.84	= 0.135627E+00	= 0.135627E+07
= 1.85	= 0.164384E+00	= 0.164384E+07
= 1.86	= 0.199239E+00	= 0.199239E+07

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ ($\times 10^{-7}$ mho/□-V)
= 1.87	= 0.241486E+00	= 0.241486E+07
= 1.88	= 0.292688E+00	= 0.292688E+07
= 1.89	= 0.354747E+00	= 0.354747E+07
= 1.90	= 0.429965E+00	= 0.429965E+07
= 1.91	= 0.521137E+00	= 0.521137E+07
= 1.92	= 0.631635E+00	= 0.631635E+07
= 1.93	= 0.765561E+00	= 0.765561E+07
= 1.94	= 0.927885E+00	= 0.927885E+07
= 1.95	= 0.112463E+01	= 0.112463E+08
= 1.96	= 0.136308E+01	= 0.136308E+08
= 1.97	= 0.165210E+01	= 0.165210E+08
= 1.98	= 0.200240E+01	= 0.200240E+08
= 1.99	= 0.242700E+01	= 0.242700E+08
= 2.00	= 0.294160E+01	= 0.294160E+08

*

Table 8. Relation between $\dfrac{d\Delta\sigma}{dV_s}$ and V_s.

C-FOCAL,1969

01.01 FOR V=-1.00,0.01,-0.01; DO 02.00
01.02 QUIT

02.01 SET A=38.46*V
02.02 SET B=FEXP(A)
02.03 SET C=(1/B-1+5.9E-22*(B-1))/FSQT(1/B+A-1+5.9E-22*(B-A-1))
02.04 SET Y=2.4E-6*C
02.05 TYPE % 3.02,V,"   ", %,-Y,"   ", %,-Y*1E7,!
*GO

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ ($\times 10^{-7}$ mho/□-V)
=-1.00	=-0.539128E+03	=-0.539128E+10
=-0.99	=-0.444814E+03	=-0.444814E+10
=-0.98	=-0.366998E+03	=-0.366998E+10
=-0.97	=-0.302796E+03	=-0.302796E+10
=-0.96	=-0.249824E+03	=-0.249824E+10
=-0.95	=-0.206120E+03	=-0.206120E+10
=-0.94	=-0.170061E+03	=-0.170061E+10
=-0.93	=-0.140311E+03	=-0.140311E+10
=-0.92	=-0.115765E+03	=-0.115765E+10
=-0.91	=-0.955125E+02	=-0.955125E+09
=-0.90	=-0.788036E+02	=-0.788036E+09
=-0.89	=-0.650177E+02	=-0.650177E+09
=-0.88	=-0.536435E+02	=-0.536435E+09
=-0.87	=-0.442590E+02	=-0.442590E+09
=-0.86	=-0.365164E+02	=-0.365163E+09
=-0.85	=-0.301281E+02	=-0.301281E+09
=-0.84	=-0.248575E+02	=-0.248575E+09
=-0.83	=-0.205089E+02	=-0.205089E+09
=-0.82	=-0.169211E+02	=-0.169211E+09
=-0.81	=-0.139609E+02	=-0.139609E+09
=-0.80	=-0.115186E+02	=-0.115186E+09
=-0.79	=-0.950350E+01	=-0.950350E+08
=-0.78	=-0.784096E+01	=-0.784096E+08
=-0.77	=-0.646925E+01	=-0.646925E+08
=-0.76	=-0.533751E+01	=-0.533751E+08
=-0.75	=-0.440376E+01	=-0.440376E+08
=-0.74	=-0.363337E+01	=-0.363337E+08
=-0.73	=-0.299774E+01	=-0.299774E+08
=-0.72	=-0.247332E+01	=-0.247332E+08
=-0.71	=-0.204063E+01	=-0.204063E+08
=-0.70	=-0.168365E+01	=-0.168365E+08
=-0.69	=-0.138911E+01	=-0.138911E+08
=-0.68	=-0.114610E+01	=-0.114610E+08
=-0.67	=-0.945598E+00	=-0.945598E+07
=-0.66	=-0.780174E+00	=-0.780174E+07
=-0.65	=-0.643691E+00	=-0.643691E+07
=-0.64	=-0.531083E+00	=-0.531083E+07
=-0.63	=-0.438176E+00	=-0.438176E+07
=-0.62	=-0.361521E+00	=-0.361520E+07

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ ($\times 10^{-7}$ mho/□-V)
=-0.61	=-0.298276E+00	=-0.298276E+07
=-0.60	=-0.246095E+00	=-0.246095E+07
=-0.59	=-0.203043E+00	=-0.203043E+07
=-0.58	=-0.167523E+00	=-0.167523E+07
=-0.57	=-0.138217E+00	=-0.138217E+07
=-0.56	=-0.114037E+00	=-0.114037E+07
=-0.55	=-0.940871E-01	=-0.940871E+06
=-0.54	=-0.776274E-01	=-0.776274E+06
=-0.53	=-0.640473E-01	=-0.640473E+06
=-0.52	=-0.528428E-01	=-0.528428E+06
=-0.51	=-0.435984E-01	=-0.435984E+06
=-0.50	=-0.359713E-01	=-0.359713E+06
=-0.49	=-0.296785E-01	=-0.296785E+06
=-0.48	=-0.244865E-01	=-0.244865E+06
=-0.47	=-0.202028E-01	=-0.202028E+06
=-0.46	=-0.166685E-01	=-0.166685E+06
=-0.45	=-0.137525E-01	=-0.137525E+06
=-0.44	=-0.113466E-01	=-0.113466E+06
=-0.43	=-0.936167E-02	=-0.936168E+05
=-0.42	=-0.772393E-02	=-0.772393E+05
=-0.41	=-0.637271E-02	=-0.637271E+05
=-0.40	=-0.525786E-02	=-0.525786E+05
=-0.39	=-0.433805E-02	=-0.433805E+05
=-0.38	=-0.357916E-02	=-0.357916E+05
=-0.37	=-0.295302E-02	=-0.295302E+05
=-0.36	=-0.243642E-02	=-0.243642E+05
=-0.35	=-0.201020E-02	=-0.201020E+05
=-0.34	=-0.165854E-02	=-0.165854E+05
=-0.33	=-0.136840E-02	=-0.136840E+05
=-0.32	=-0.112902E-02	=-0.112902E+05
=-0.31	=-0.931519E-03	=-0.931519E+04
=-0.30	=-0.768571E-03	=-0.768571E+04
=-0.29	=-0.634130E-03	=-0.634130E+04
=-0.28	=-0.523211E-03	=-0.523211E+04
=-0.27	=-0.431698E-03	=-0.431698E+04
=-0.26	=-0.356198E-03	=-0.356198E+04
=-0.25	=-0.293909E-03	=-0.293909E+04
=-0.24	=-0.242520E-03	=-0.242520E+04
=-0.23	=-0.200126E-03	=-0.200126E+04
=-0.22	=-0.165153E-03	=-0.165153E+04
=-0.21	=-0.136303E-03	=-0.136304E+04
=-0.20	=-0.112507E-03	=-0.112507E+04
=-0.19	=-0.928797E-04	=-0.928797E+03
=-0.18	=-0.766934E-04	=-0.766934E+03
=-0.17	=-0.633465E-04	=-0.633465E+03
=-0.16	=-0.523430E-04	=-0.523430E+03
=-0.15	=-0.432734E-04	=-0.432734E+03
=-0.14	=-0.358000E-04	=-0.358001E+03
=-0.13	=-0.296440E-04	=-0.296440E+03

V_s (volt)	$d\Delta\sigma/dV_s$ (mho/□-V)	$d\Delta\sigma/dV_s$ (x 10^{-7} mho/□-V)
=-0.12	=-0.245751E-04	=-0.245751E+03
=-0.11	=-0.204032E-04	=-0.204032E+03
=-0.10	=-0.169715E-04	=-0.169715E+03
=-0.09	=-0.141501E-04	=-0.141501E+03
=-0.08	=-0.118318E-04	=-0.118318E+03
=-0.07	=-0.992784E-05	=-0.992785E+02
=-0.06	=-0.836495E-05	=-0.836495E+02
=-0.05	=-0.708241E-05	=-0.708241E+02
=-0.04	=-0.603004E-05	=-0.603004E+02
=-0.03	=-0.516636E-05	=-0.516636E+02
=-0.02	=-0.445713E-05	=-0.445713E+02
=-0.01	=-0.387413E-05	=-0.387413E+02

*

3.4 <u>The Approximated Calculation of the Relation Between</u> <u>the Surface Potential, V_s, and the Applied Electric</u> <u>Potential, V_A</u>

Consider the system which consists of metal-dielectric material-semiconductor as illustrated in Figure 17. By applying equations (39) and (63), we have the following relations:

$$\varepsilon_d E_d = \varepsilon_s E_s$$

$$\varepsilon_d \frac{(V_A - V_s)}{Z_d} = \varepsilon_s E_s = \frac{Q_s}{\varepsilon_o}$$

Therefore,

$$\varepsilon_o \varepsilon_d \frac{(V_A - V_s)}{Z_d} = Q_s =$$

$$= \pm (2kT\varepsilon_o \varepsilon_s p_o)^{\frac{1}{2}} [(e^{-\beta V}s + \beta V_s - 1) + \frac{n_o}{p_o}(e^{\beta V}s - \beta V_s - 1)]^{\frac{1}{2}}$$

$$V_A = V_s \pm \frac{Z_d}{\varepsilon_o \varepsilon_d}(2kT\varepsilon_o \varepsilon_s p_o)^{\frac{1}{2}}\left[(e^{-\beta V}s + \beta V_s - 1) + \frac{n_o}{p_o}(e^{\beta V}s - \beta V_s - 1)\right]^{\frac{1}{2}}.$$

From the above expression, the calculations of applied electric potential, V_A, as the function of surface potential, V_s, were done and the result is given in Figure 18, and the numerical results are also shown in the Tables 9, and 10.
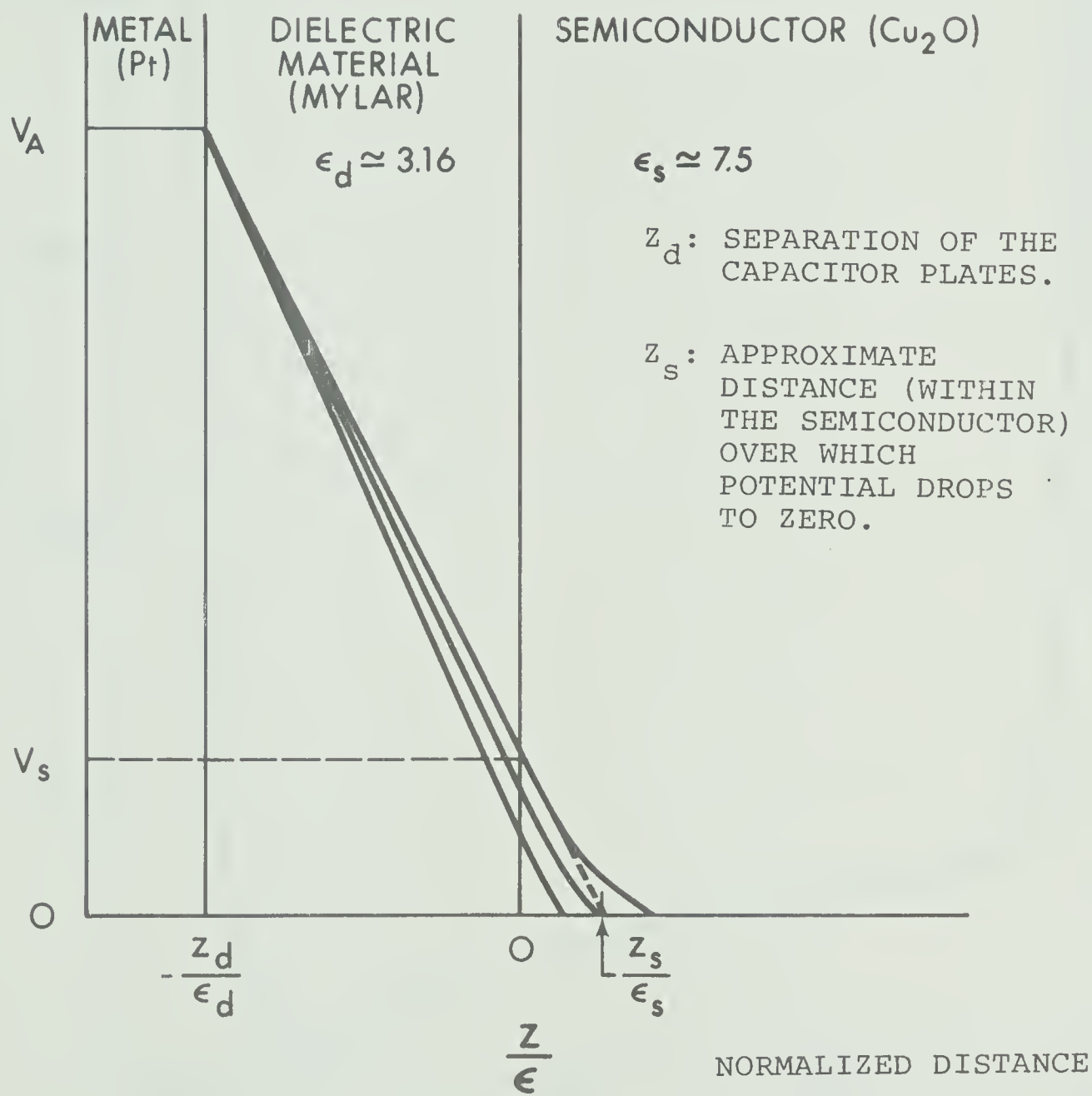
Figure 17. Schematic diagram of system of metal--

dielectric material--semiconductor.

Figure 18. Theoretical curve of $|V_A|$ vs V_S.

Table 9. Relation between V_S and V_A.

```
C-FOCAL,1969

01.01 FOR V=0.00,0.01,2.00; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=1.25E6
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET O=A*FSQT(D+5.9E-22*G)
02.07 SET Y=V+B*O
02.08 TYPE % 3.02,V,"          ", %,O,"          ", % 7.06,Y,!
*GO
```

V$_S$ (volt)	V$_A$ (volt)	
= 0.00	= 0.000000E+00	= 0.000000
= 0.01	= 0.212645E-05	= 2.668060
= 0.02	= 0.401248E-05	= 5.035600
= 0.03	= 0.569926E-05	= 7.154080
= 0.04	= 0.722032E-05	= 9.065400
= 0.05	= 0.860292E-05	= 10.80370
= 0.06	= 0.986928E-05	= 12.39660
= 0.07	= 0.110375E-04	= 13.86690
= 0.08	= 0.121224E-04	= 15.23300
= 0.09	= 0.131361E-04	= 16.51010
= 0.10	= 0.140885E-04	= 17.71060
= 0.11	= 0.149879E-04	= 18.84480
= 0.12	= 0.158410E-04	= 19.92130
= 0.13	= 0.166536E-04	= 20.94700
= 0.14	= 0.174303E-04	= 21.92790
= 0.15	= 0.181752E-04	= 22.86900
= 0.16	= 0.188916E-04	= 23.77450
= 0.17	= 0.195823E-04	= 24.64790
= 0.18	= 0.202499E-04	= 25.49240
= 0.19	= 0.208964E-04	= 26.31050
= 0.20	= 0.215236E-04	= 27.10460
= 0.21	= 0.221332E-04	= 27.87650
= 0.22	= 0.227266E-04	= 28.62820
= 0.23	= 0.233048E-04	= 29.36100
= 0.24	= 0.238691E-04	= 30.07640
= 0.25	= 0.244204E-04	= 30.77550
= 0.26	= 0.249595E-04	= 31.45940
= 0.27	= 0.254872E-04	= 32.12900
= 0.28	= 0.260042E-04	= 32.78530
= 0.29	= 0.265112E-04	= 33.42900
= 0.30	= 0.270086E-04	= 34.06080
= 0.31	= 0.274971E-04	= 34.68130
= 0.32	= 0.279770E-04	= 35.29120
= 0.33	= 0.284488E-04	= 35.89100
= 0.34	= 0.289129E-04	= 36.48110
= 0.35	= 0.293697E-04	= 37.06210

V_s (volt)		V_A (volt)
= 0.36	= 0.298195E-04	= 37.63440
= 0.37	= 0.302626E-04	= 38.19820
= 0.38	= 0.306993E-04	= 38.75410
= 0.39	= 0.311299E-04	= 39.30240
= 0.40	= 0.315546E-04	= 39.84330
= 0.41	= 0.319737E-04	= 40.37710
= 0.42	= 0.323873E-04	= 40.90420
= 0.43	= 0.327958E-04	= 41.42470
= 0.44	= 0.331992E-04	= 41.93900
= 0.45	= 0.335977E-04	= 42.44720
= 0.46	= 0.339916E-04	= 42.94950
= 0.47	= 0.343810E-04	= 43.44630
= 0.48	= 0.347660E-04	= 43.93750
= 0.49	= 0.351468E-04	= 44.42350
= 0.50	= 0.355235E-04	= 44.90440
= 0.51	= 0.358963E-04	= 45.38040
= 0.52	= 0.362652E-04	= 45.85160
= 0.53	= 0.366305E-04	= 46.31810
= 0.54	= 0.369921E-04	= 46.78010
= 0.55	= 0.373502E-04	= 47.23770
= 0.56	= 0.377049E-04	= 47.69110
= 0.57	= 0.380563E-04	= 48.14040
= 0.58	= 0.384045E-04	= 48.58560
= 0.59	= 0.387495E-04	= 49.02690
= 0.60	= 0.390916E-04	= 49.46450
= 0.61	= 0.394306E-04	= 49.89830
= 0.62	= 0.397668E-04	= 50.32850
= 0.63	= 0.401001E-04	= 50.75520
= 0.64	= 0.404307E-04	= 51.17840
= 0.65	= 0.407586E-04	= 51.59830
= 0.66	= 0.410839E-04	= 52.01490
= 0.67	= 0.414066E-04	= 52.42830
= 0.68	= 0.417269E-04	= 52.83860
= 0.69	= 0.420447E-04	= 53.24590
= 0.70	= 0.423601E-04	= 53.65020
= 0.71	= 0.426732E-04	= 54.05150
= 0.72	= 0.429840E-04	= 54.45000
= 0.73	= 0.432926E-04	= 54.84580
= 0.74	= 0.435990E-04	= 55.23870
= 0.75	= 0.439032E-04	= 55.62910
= 0.76	= 0.442054E-04	= 56.01680
= 0.77	= 0.445055E-04	= 56.40190
= 0.78	= 0.448036E-04	= 56.78450
= 0.79	= 0.450997E-04	= 57.16470
= 0.80	= 0.453939E-04	= 57.54240
= 0.81	= 0.456862E-04	= 57.91780
= 0.82	= 0.459767E-04	= 58.29080
= 0.83	= 0.462653E-04	= 58.66160
= 0.84	= 0.465521E-04	= 59.03020

V_s (volt)		V_A (volt)
= 0.85	= 0.468372E-04	= 59.39650
= 0.86	= 0.471205E-04	= 59.76070
= 0.87	= 0.474022E-04	= 60.12280
= 0.88	= 0.476822E-04	= 60.48280
= 0.89	= 0.479605E-04	= 60.84070
= 0.90	= 0.482373E-04	= 61.19660
= 0.91	= 0.485125E-04	= 61.55060
= 0.92	= 0.487861E-04	= 61.90260
= 0.93	= 0.490582E-04	= 62.25270
= 0.94	= 0.493288E-04	= 62.60100
= 0.95	= 0.495979E-04	= 62.94740
= 0.96	= 0.498656E-04	= 63.29200
= 0.97	= 0.501318E-04	= 63.63480
= 0.98	= 0.503966E-04	= 63.97580
= 0.99	= 0.506601E-04	= 64.31510
= 1.00	= 0.509222E-04	= 64.65270
= 1.01	= 0.511829E-04	= 64.98870
= 1.02	= 0.514424E-04	= 65.32300
= 1.03	= 0.517005E-04	= 65.65560
= 1.04	= 0.519574E-04	= 65.98670
= 1.05	= 0.522130E-04	= 66.31620
= 1.06	= 0.524674E-04	= 66.64420
= 1.07	= 0.527205E-04	= 66.97070
= 1.08	= 0.529726E-04	= 67.29570
= 1.09	= 0.532235E-04	= 67.61940
= 1.10	= 0.534733E-04	= 67.94160
= 1.11	= 0.537221E-04	= 68.26260
= 1.12	= 0.539699E-04	= 68.58240
= 1.13	= 0.542169E-04	= 68.90110
= 1.14	= 0.544631E-04	= 69.21890
= 1.15	= 0.547089E-04	= 69.53620
= 1.16	= 0.549545E-04	= 69.85320
= 1.17	= 0.552004E-04	= 70.17050
= 1.18	= 0.554470E-04	= 70.48880
= 1.19	= 0.556954E-04	= 70.80920
= 1.20	= 0.559467E-04	= 71.13340
= 1.21	= 0.562030E-04	= 71.46380
= 1.22	= 0.564669E-04	= 71.80370
= 1.23	= 0.567424E-04	= 72.15810
= 1.24	= 0.570354E-04	= 72.53430
= 1.25	= 0.573544E-04	= 72.94300
= 1.26	= 0.577117E-04	= 73.39960
= 1.27	= 0.581252E-04	= 73.92650
= 1.28	= 0.586210E-04	= 74.55630
= 1.29	= 0.592366E-04	= 75.33580
= 1.30	= 0.600255E-04	= 76.33190
= 1.31	= 0.610639E-04	= 77.63990
= 1.32	= 0.624581E-04	= 79.39270
= 1.33	= 0.643547E-04	= 81.77340

V_s (volt)		V_A (volt)
= 1.34	= 0.669504E-04	= 85.02800
= 1.35	= 0.705021E-04	= 89.47760
= 1.36	= 0.753342E-04	= 95.52780
= 1.37	= 0.818410E-04	= 103.6710
= 1.38	= 0.904870E-04	= 114.4890
= 1.39	= 0.101804E-03	= 128.6450
= 1.40	= 0.116398E-03	= 146.8980
= 1.41	= 0.134960E-03	= 170.1100
= 1.42	= 0.158289E-03	= 199.2820
= 1.43	= 0.187331E-03	= 235.5940
= 1.44	= 0.223217E-03	= 280.4620
= 1.45	= 0.267315E-03	= 335.5930
= 1.46	= 0.321279E-03	= 403.0590
= 1.47	= 0.387129E-03	= 485.3820
= 1.48	= 0.467316E-03	= 585.6260
= 1.49	= 0.564824E-03	= 707.5200
= 1.50	= 0.683267E-03	= 855.5840
= 1.51	= 0.827046E-03	= 1035.320
= 1.52	= 0.100150E-02	= 1253.390
= 1.53	= 0.121309E-02	= 1517.900
= 1.54	= 0.146968E-02	= 1838.640
= 1.55	= 0.178078E-02	= 2227.530
= 1.56	= 0.215793E-02	= 2698.970
= 1.57	= 0.261512E-02	= 3270.470
= 1.58	= 0.316932E-02	= 3963.240
= 1.59	= 0.384107E-02	= 4802.930
= 1.60	= 0.465530E-02	= 5820.720
= 1.61	= 0.564219E-02	= 7054.350
= 1.62	= 0.683841E-02	= 8549.640
= 1.63	= 0.828826E-02	= 10361.90
= 1.64	= 0.100455E-01	= 12558.60
= 1.65	= 0.121754E-01	= 15220.90
= 1.66	= 0.147570E-01	= 18447.90
= 1.67	= 0.178859E-01	= 22359.10
= 1.68	= 0.216783E-01	= 27099.50
= 1.69	= 0.262747E-01	= 32845.10
= 1.70	= 0.318459E-01	= 39809.10
= 1.71	= 0.385982E-01	= 48249.50
= 1.72	= 0.467823E-01	= 58479.60
= 1.73	= 0.567016E-01	= 70878.70
= 1.74	= 0.687248E-01	= 85907.80
= 1.75	= 0.832967E-01	= 104123.0
= 1.76	= 0.100958E+00	= 126200.0
= 1.77	= 0.122365E+00	= 152957.0
= 1.78	= 0.148310E+00	= 185389.0
= 1.79	= 0.179756E+00	= 224697.0
= 1.80	= 0.217870E+00	= 272339.0
= 1.81	= 0.264066E+00	= 330084.0
= 1.82	= 0.320059E+00	= 400076.0

V_S (volt)		V_A (volt)
= 1.83	= 0.387922E+00	= 484904.0
= 1.84	= 0.470174E+00	= 587719.0
= 1.85	= 0.569866E+00	= 712334.0
= 1.86	= 0.690696E+00	= 863371.0
= 1.87	= 0.837150E+00	= 1046440
= 1.88	= 0.101465E+01	= 1268320
= 1.89	= 0.122979E+01	= 1537240
= 1.90	= 0.149055E+01	= 1863180
= 1.91	= 0.180661E+01	= 2258260
= 1.92	= 0.218967E+01	= 2737080
= 1.93	= 0.265395E+01	= 3317430
= 1.94	= 0.321667E+01	= 4020830
= 1.95	= 0.389870E+01	= 4873380
= 1.96	= 0.472535E+01	= 5906690
= 1.97	= 0.572728E+01	= 7159100
= 1.98	= 0.694164E+01	= 8677050
= 1.99	= 0.841358E+01	= 0.1051700E+08
= 2.00	= 0.101975E+02	= 0.1274692E+08

*

Table 10. Relation between V_S and V_A.

```
C-FOCAL,1969

01.01 FOR V=-0.75,0.01,-0.01; DO 02.00
01.02 QUIT

02.01 SET A=8.32E-6
02.02 SET B=1.25E6
02.03 SET C=38.46*V
02.04 SET D=FEXP(-C)+C-1
02.05 SET G=FEXP(C)-C-1
02.06 SET O=A*FSQT(D+5.9E-22*G)
02.07 SET Y=V-B*O
02.08 TYPE % 3.02,V,"          ", %,O,"          ", % 7.06,Y,!
*GO
```

V_s (volt)		V_A (volt)
=-0.75	= 0.152663E+02	=-0.1908291E+08
=-0.74	= 0.125956E+02	=-0.1574460E+08
=-0.73	= 0.103921E+02	=-0.1299020E+08
=-0.72	= 0.857416E+01	=-0.1071770E+08
=-0.71	= 0.707418E+01	=-8842720
=-0.70	= 0.583661E+01	=-7295770
=-0.69	= 0.481555E+01	=-6019440
=-0.68	= 0.397312E+01	=-4966400
=-0.67	= 0.327806E+01	=-4097570
=-0.66	= 0.270460E+01	=-3389750
=-0.65	= 0.223145E+01	=-2789310
=-0.64	= 0.184108E+01	=-2301350
=-0.63	= 0.151900E+01	=-1898750
=-0.62	= 0.125326E+01	=-1566580
=-0.61	= 0.103402E+01	=-1292520
=-0.60	= 0.853127E+00	=-1066410
=-0.59	= 0.703880E+00	=-879850.0
=-0.58	= 0.580743E+00	=-725930.0
=-0.57	= 0.479147E+00	=-598935.0
=-0.56	= 0.395326E+00	=-494158.0
=-0.55	= 0.326167E+00	=-407709.0
=-0.54	= 0.269107E+00	=-336385.0
=-0.53	= 0.222029E+00	=-277537.0
=-0.52	= 0.183188E+00	=-228985.0
=-0.51	= 0.151140E+00	=-188926.0
=-0.50	= 0.124700E+00	=-155876.0
=-0.49	= 0.102885E+00	=-128607.0
=-0.48	= 0.848861E-01	=-106108.0
=-0.47	= 0.700360E-01	=-87545.50
=-0.46	= 0.577840E-01	=-72230.50
=-0.45	= 0.476752E-01	=-59594.40
=-0.44	= 0.393349E-01	=-49169.00
=-0.43	= 0.324536E-01	=-40567.50
=-0.42	= 0.267761E-01	=-33470.60
=-0.41	= 0.220919E-01	=-27615.30
=-0.40	= 0.182271E-01	=-22784.30

V_s (volt)		V_A (volt)
$=-0.39$	$= 0.150384E-01$	$=-18798.50$
$=-0.38$	$= 0.124076E-01$	$=-15509.90$
$=-0.37$	$= 0.102370E-01$	$=-12796.60$
$=-0.36$	$= 0.844612E-02$	$=-10558.00$
$=-0.35$	$= 0.696852E-02$	$=-8711.000$
$=-0.34$	$= 0.574942E-02$	$=-7187.120$
$=-0.33$	$= 0.474358E-02$	$=-5929.810$
$=-0.32$	$= 0.391370E-02$	$=-4892.450$
$=-0.31$	$= 0.322899E-02$	$=-4036.550$
$=-0.30$	$= 0.266406E-02$	$=-3330.380$
$=-0.29$	$= 0.219795E-02$	$=-2747.730$
$=-0.28$	$= 0.181338E-02$	$=-2267.000$
$=-0.27$	$= 0.149607E-02$	$=-1870.350$
$=-0.26$	$= 0.123425E-02$	$=-1543.080$
$=-0.25$	$= 0.101823E-02$	$=-1273.030$
$=-0.24$	$= 0.839972E-03$	$=-1050.210$
$=-0.23$	$= 0.692883E-03$	$=-866.3350$
$=-0.22$	$= 0.571503E-03$	$=-714.5980$
$=-0.21$	$= 0.471330E-03$	$=-589.3730$
$=-0.20$	$= 0.388652E-03$	$=-486.0150$
$=-0.19$	$= 0.320403E-03$	$=-400.6940$
$=-0.18$	$= 0.264054E-03$	$=-330.2480$
$=-0.17$	$= 0.217519E-03$	$=-272.0690$
$=-0.16$	$= 0.179076E-03$	$=-224.0050$
$=-0.15$	$= 0.147303E-03$	$=-184.2780$
$=-0.14$	$= 0.121027E-03$	$=-151.4230$
$=-0.13$	$= 0.992792E-04$	$=-124.2290$
$=-0.12$	$= 0.812618E-04$	$=-101.6970$
$=-0.11$	$= 0.663148E-04$	$=-83.00360$
$=-0.10$	$= 0.538944E-04$	$=-67.46800$
$=-0.09$	$= 0.435517E-04$	$=-54.52970$
$=-0.08$	$= 0.349168E-04$	$=-43.72600$
$=-0.07$	$= 0.276848E-04$	$=-34.67600$
$=-0.06$	$= 0.216046E-04$	$=-27.06580$
$=-0.05$	$= 0.164698E-04$	$=-20.63730$
$=-0.04$	$= 0.121107E-04$	$=-15.17840$
$=-0.03$	$= 0.838824E-05$	$=-10.51530$
$=-0.02$	$= 0.518829E-05$	$=-6.505360$
$=-0.01$	$= 0.241765E-05$	$=-3.032060$
*		

CHAPTER IV

THE APPARATUS AND EXPERIMENTAL PROCEDURE

4.1   The Apparatus and the Sample

Figure 19 gives a schematic diagram of the apparatus used for the experiment. The sample and sample holder were mounted inside the vacuum chamber. The specimen is a rectangular bar of single crystal cuprous oxide with the size of 1.2 x 2.5 x 8.0 mm, with the resistance along the longest side of about 2.0×10^6 ohm, and with contacts of platinum to the ends (see Figure 20). The dielectric spacer between the sample and the platinum electrode is a mylar plate of 0.004 cm thickness. The sample resistance was measured by means of the d. c. wheatstone bridge (see Figure 19). The electric field applied to the sample is produced by batteries.
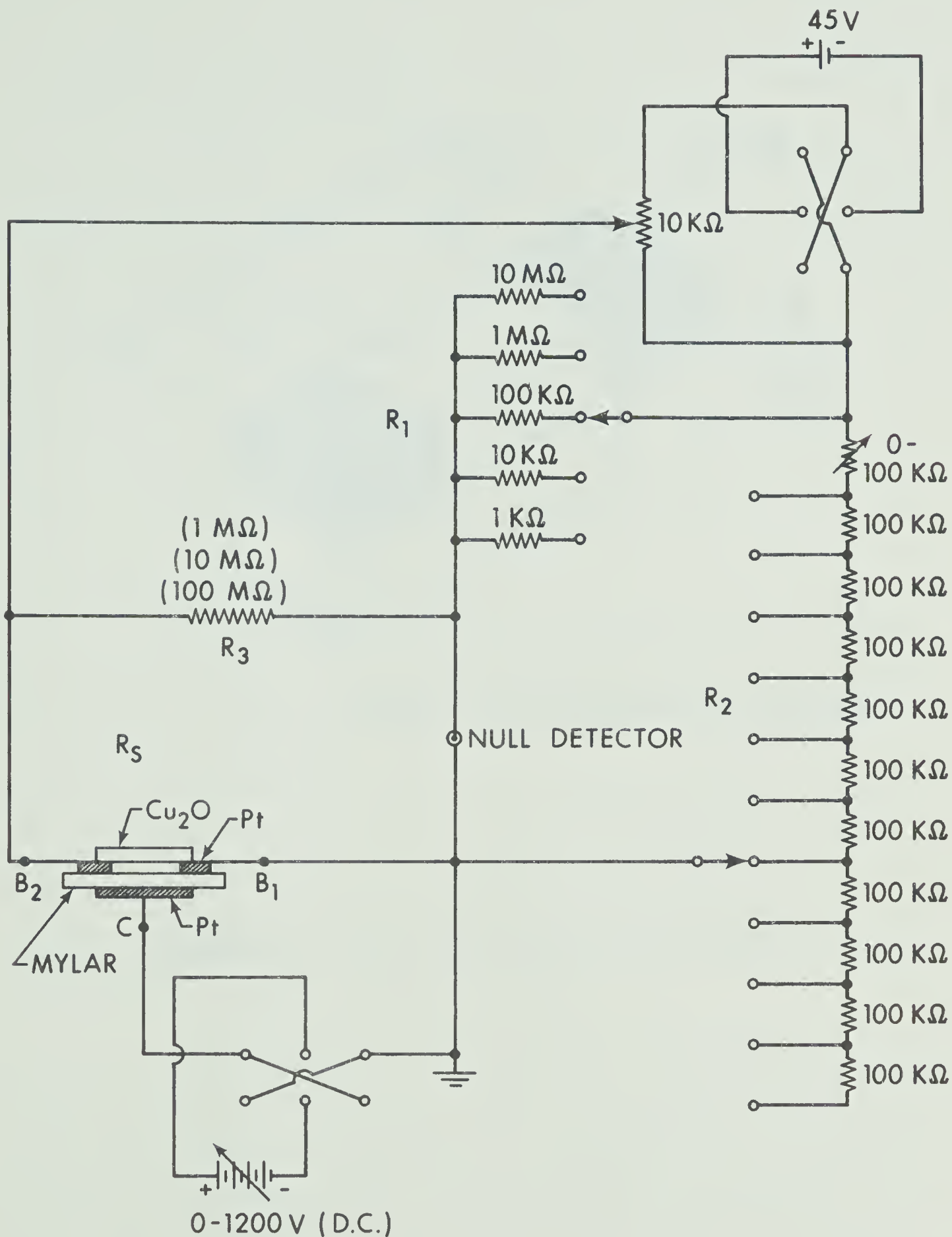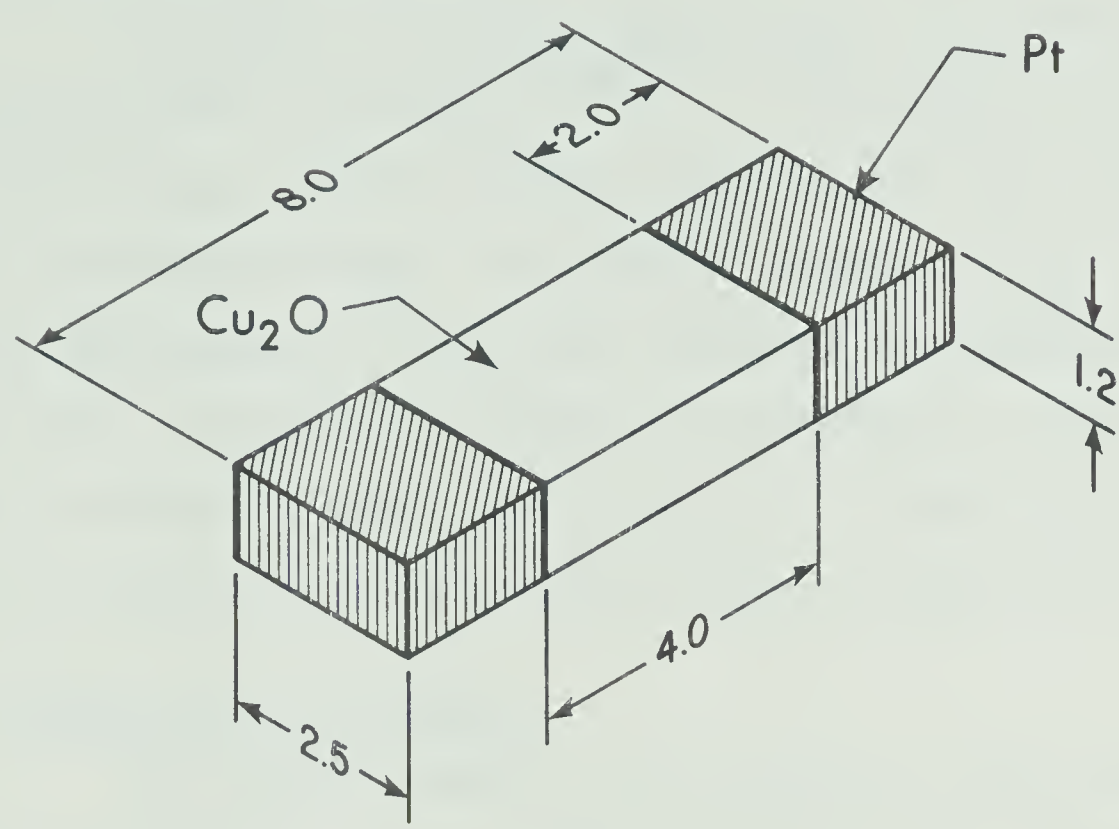
Figure 19. Schematic diagram of apparatus for measuring field effect.

NOTE : ALL DIMENSIONS IN millimeters

Figure 20. Shape and size of the sample.

4.2   The Sample Preparation

Crystals of cuprous oxide (Cu_2O) were grown by the grain growth technique[25,26,29]. The samples used were cut from larger single crystals and provided with sputtered platinum contacts. The entire theory of Cu_2O as a defect semiconductor[30] has been based on the experimental fact that, regardless of method of preparation, the material is always p-type. This in turn is blamed on an excess of oxygen beyond the stoichiometric proportions.

4.3   Experimental Procedure

The sample chamber was evacuated to the pressure of 2×10^{-6} mm Hg. In the measurements of the field-effect the standard method was used: a constant voltage (up to 1200 V) was applied to a capacitor, one electrode of which was the sample and the other the metal deposited on the mylar spacer. The measured capacitance of the whole system was 20 - 25 pF, at a frequency of 1 kc as measured by the impedance bridge (GR-type 1650 A).

For each new applied voltage the system is allowed to reach equilibrium. The change in the sample resistance was measured by means of an unbalanced d. c. bridge. Readings were taken 2 min after applying the voltage. During the experiment, the measuring voltage across the sample is kept small (about 5.0 V or less) compared to

that of which applied at the capacitor so as to maintain
the entire surface at effectively the same potential.

CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Experimental Results

In the experiment, we can apply more than 1000 V
of positive potential to the platinum plate-electrode of
the capacitor and up to 700 V of negative potential. The
experimental data of the measuring resistances of the sample
at various applied voltages are presented in Tables 11 and
12. From these tables, the surface conductance, $\Delta\sigma$, is
plotted against the applied voltage, V_A, as shown in Figure
21. It is seen that in our experiment, the field effect
existed in our chosen cuprous oxide sample. The minimum
value of surface conductance, $(\Delta\sigma)_{min}$, is -4.2×10^{-9}
mho/□ at a value of the applied potential of 560 V.
The presence of a minimum in the experimental field effect
curve allowed us to compare the experimental data with the
calculated curves and to find the dependence of the sur-
face band curvature on the applied voltage.

Figure 22 shows both theoretical and experimen-
tal curves of surface conductance, $\Delta\sigma$, versus charge den-
sities (Q_S, Q_T). The abscissa is now Q_T. The experimental
curve has been adjusted vertically so that its minimum
occurs at the minimum of the theoretical curve. This
adjustment is significant since the minimum conductance,

$(\Delta\sigma)_{min}$, has a unique value independent of charge in sur-
face states, Q_{ss}, which is assumed to be immobile. Having
made this adjustment, the experimental surface conductance
has an absolute significance, in terms of Q_s and V_s. The
difference between the experimental and theoretical curves
at a given value of $\Delta\sigma$ is just Q_{ss}. Thus by comparing the
two curves one can obtain Q_{ss} as a function of V_s. Figure
23 is a plot of this result. As indicated, the surface
states are neutral when $V_s \simeq 1.38$ V. The shape of the curve
is related to, but does not uniquely determine, the energy
distribution of the surface states. The distribution may
be continuous, in which case the slope of the curve is the
surface state density involving the minimum number of
states; or the distribution may be discrete, perhaps as
described by Bardeen and Brattain[31] in their model of the
surface. This later possibility would predict a curve sim-
ilar in shape to Figure 23.

Table 11. Experimental data.

$(V_A = 0 \rightarrow +1000 \text{ V})$

V_A	$R_S \, (\times 10^6 \, \Omega)$	$\sigma \times (10^{-7} \, \text{mho})$	$\Delta\sigma \times (10^{-9} \, \text{mho}/\square)$
0	1.9610	5.0994	0
+50	1.9620	5.0968	-0.26
+100	1.9627	5.0950	-0.44
+150	1.9649	5.0893	-1.01
+200	1.9660	5.0849	-1.45
+250	1.9684	5.0803	-1.91
+300	1.9725	5.0697	-2.97
+350	1.9733	5.0676	-3.18
+400	1.9741	5.0656	-3.38
+450	1.9752	5.0627	-3.67
+500	1.9762	5.0602	-3.92
+520	1.9767	5.0589	-4.05
+540	1.9771	5.0578	-4.16
+560	1.9773	5.0573	-4.21
+580	1.9767	5.0589	-4.05
+600	1.9769	5.0584	-4.10
+620	1.9733	5.0676	-3.18
+640	1.9718	5.0715	-2.79
+660	1.9706	5.0746	-2.48
+680	1.9697	5.0769	-2.25
+700	1.9685	5.0800	-1.94
+720	1.9670	5.0839	-1.55
+740	1.9669	5.0842	-1.52
+760	1.9668	5.0844	-1.39
+780	1.9664	5.0855	-1.21
+800	1.9657	5.0873	-1.19
+820	1.9656	5.0875	-1.08
+840	1.9652	5.0886	-0.25
+860	1.9584	5.1062	0.68
+880	1.9588	5.1052	0.58
+900	1.9582	5.1068	0.74
+920	1.9575	5.1086	0.92
+940	1.9572	5.1094	1.00
+960	1.9573	5.1091	0.97
+980	1.9574	5.1089	0.95
+1000	1.9559	5.1128	1.34

Table 12.   Experimental data.

$(V_A = 0 \rightarrow -700V)$

| V_A	R_S x $(10^6 \Omega)$	σ x $(10^{-7}$ mho)	$\Delta\sigma$ x $(10^{-9}$ mho/□)
0	1.9399	5.1549	0
-50	1.9394	5.1562	0.13
-100	1.9397	5.1554	0.05
-150	1.9388	5.1578	0.29
-200	1.9385	5.1586	0.37
-250	1.9385	5.1586	0.37
-300	1.9365	5.1640	0.91
-350	1.9358	5.1658	1.09
-400	1.9361	5.1650	1.01
-450	1.9364	5.1643	0.94
-500	1.9358	5.1659	1.10
-520	1.9363	5.1645	0.96
-540	1.9369	5.1629	0.80
-560	1.9386	5.1584	0.35
-580	1.9399	5.1550	0.01
-600	1.9408	5.1526	-0.23
-620	1.9406	5.1531	-0.18
-640	1.9407	5.1529	-0.20
-660	1.9402	5.1542	-0.07
-680	1.9387	5.1582	0.33
-700	1.9368	5.1638	0.89
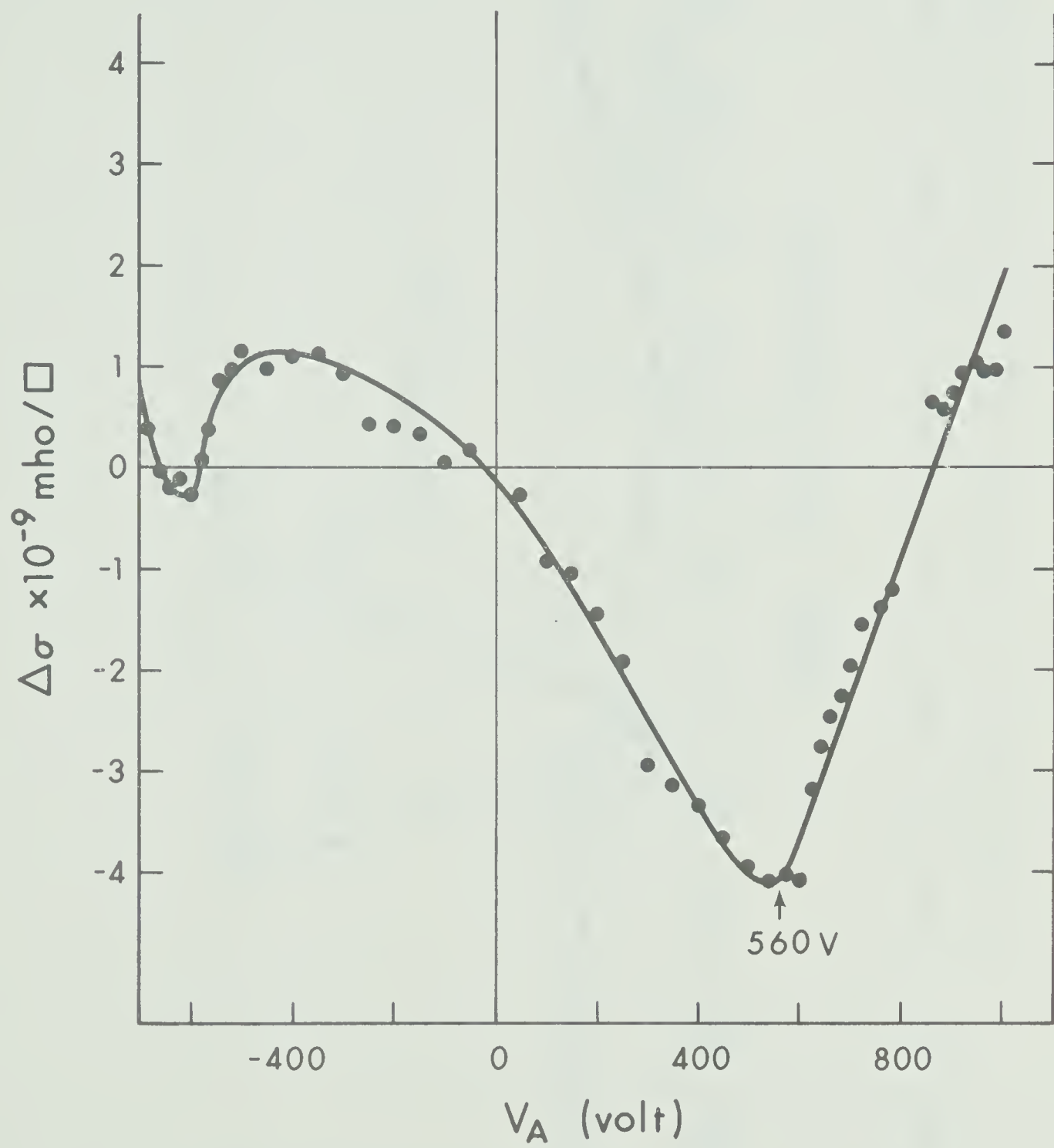
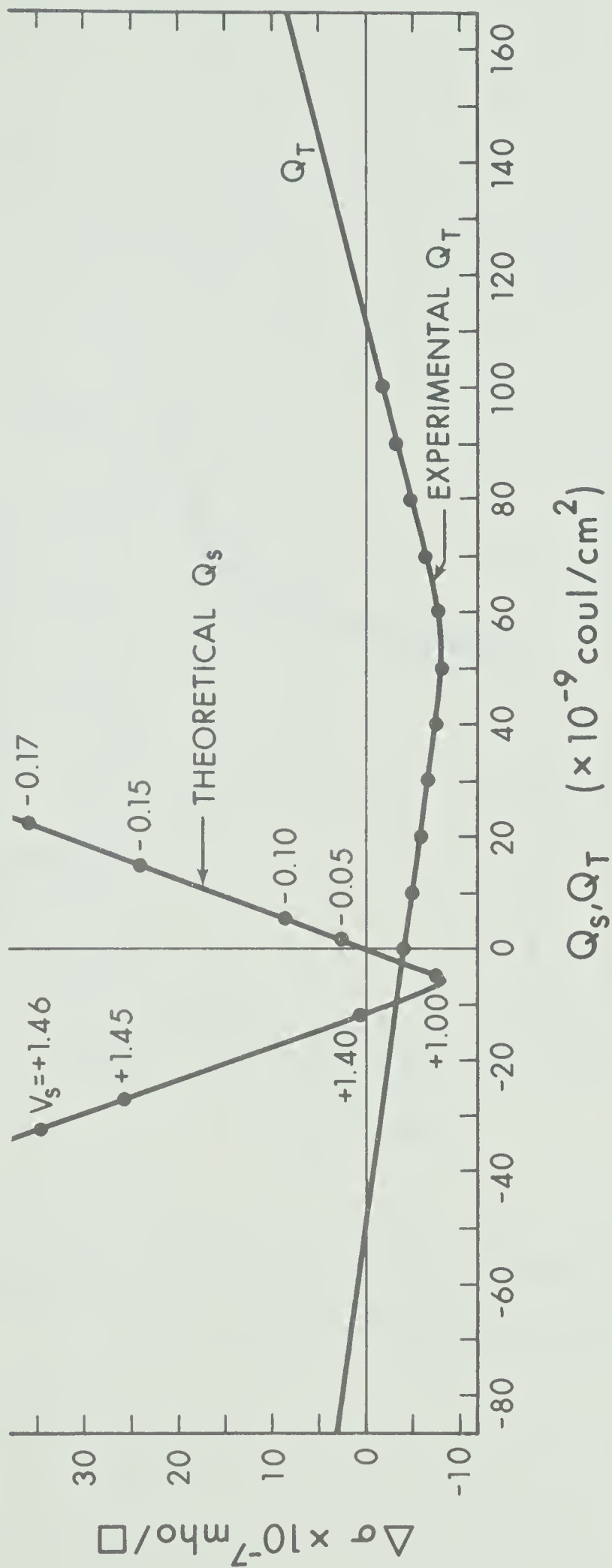Figure 21. Experimental curve of $\Delta\sigma$ vs V_A.

Figure 22.   Theoretical dependence of surface conductance on space charge

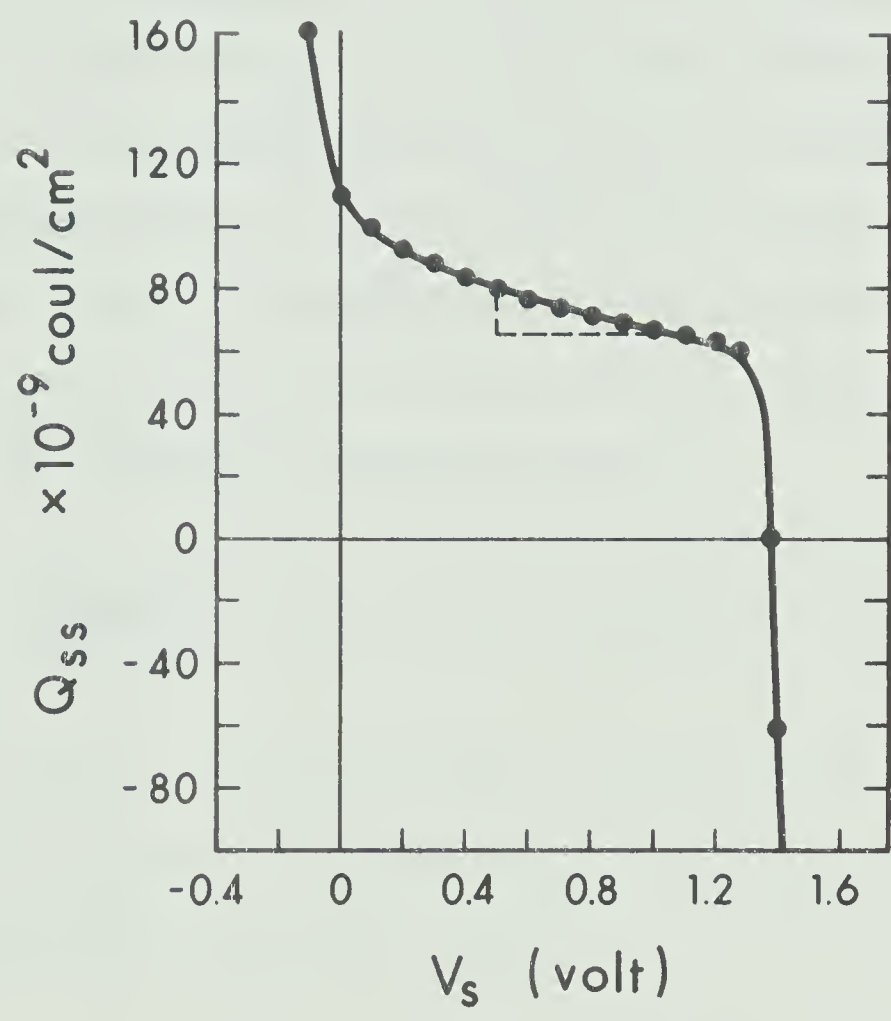and experimentally determined dependence on total charge.

Figure 23. Charge in surface states as a function of surface potential.

5.2 Discussion

The Figure 23 shows the experimental dependence of the surface charge Q_{ss} on the surface band curvature V_s. The nature of the surface energy levels in cuprous oxide is clearly apparent: as the band curvature varies from $V_s = 0$ volt to $V_s = 1.27$ volt, the surface-level charge decreases. The dependence of Q_{ss} on V_s is rather smooth at room temperature. In this case, the energy distribution of the surface states seems to be continuous. The surface state density per unit potential (N_{ss}) is then obtained by graphical differentiation:

$$N_{ss} = \frac{1}{q}\left(\frac{\partial Q_{ss}}{\partial V_s}\right)_V \simeq 1.75 \times 10^{11} \text{ states/cm}^2 - \text{volt.}$$

For the discrete model of the distribution of the surface states, the experimental curve $Q_{ss} = f(V_s)$ can be described by (see Sze[14], Peka[32])

$$Q_{ss}(V_s) = \sum_{i=1}^{k} \frac{qN_{sD}^i}{g\exp\left(\frac{E_F - E_t}{kT}\right) + 1} - \sum_{i=1}^{k} \frac{qN_{sA}^i}{\left(1/g\right)\exp\left(\frac{E_t - E_F}{kT}\right) + 1}$$

where N_{sD}^i and N_{sA}^i are, respectively, the density of surface donor and acceptor states; E_t is the energy of the surface states and g is the ground state degeneracy.

In principle, with suitably selected surface

state parameters, we can calculate the total theoretical

dependence of Q_{ss} on V_s from values of the parameters N^i

and E_t by using the above equation. Then, inversely, the

density and energy position of each state could be deter-

mined[32] from the parts of the curve separated by practi-

cally horizontal plateaus. The type of level (donor or

acceptor) is found from the sign of the charge localized

at the surface states ($Q_{ss} < 0$ represents surface acceptor

states, and $Q_{ss} > 0$ represents surface donor states).

5.3 Conclusion

The main purposes of this project were first to

build and test equipment for field effect measurements,

secondly to review the basic theory of the subject matter

and to study the characteristics of the field effect of

single crystals of cuprous oxide prepared in our labora-

tory. We repeated, at room temperature, measurements done

elsewhere[27,32]. We succeeded in finding the minimum in

the experimental dependence of the surface conductance on

the applied voltage which allowed us to study both the

potential of the surface and the distribution of charge in

surface states as shown in Figure 23, we then obtained the

surface state density, $N_{ss} \simeq 1.75 \times 10^{11}$ states/cm^2 - volt,

which is in the same order as the surface acceptor state

density as given by Peka[32] (1×10^{11}, 3×10^{11}, 8×10^{11}

states/cm^2 - volt). But from the sign of the charge dis-
tribution localized at the surface states (Figure 23), we
conclude the existence of the donor rather than the accep-
tor type states. Since the spectrum of slow surface state
charges is a smooth function of the surface potential, the
distribution of the surface energy levels in our cuprous
oxide sample should be continuous rather than discrete ones
as proposed by Peka[27,32]. Most likely this is the individ-
ual property of our samples.

Other experiments were performed by connecting a
recorder to the output of the null-detector. Voltage
changes reflecting variations in surface conductance were
recorded on a fast d. c. recorder (MFE Model M-20 CAHA).
The field-effect time constant of the slow-states is seen
on the recording paper. The field-effect time constant is
arbitrarily defined as the time required for the initial
observed conductance change to decay to 60 percent of its
original value. The time constants of the samples at the
slow states range from 5 min. to 15 min. The investiga-
tion of field effect time constants will allow us to study
about the charge transfer mechanism from the bulk of the
sample to the various types of states at the surface.

The data on the field-effect time constant were
collected but the detailed analysis has not been done due
to time limitations imposed by pressures to return to

Thailand.

5.4 Suggestions for Further Work

A most interesting extension of the present experiments would be the transient method (with pulse d. c. and a. c. fields). This method can be studied in the following:

1. D. C. or low-frequency fields: for studying the charge transfer mechanism between the slow states and the underlying space-charge region.

2. Higher frequency fields: which eliminate the effect of slow states which at the same time, permitting the fast states to maintain equilibrium with the space-charge region.

3. Short pulses and very high frequency fields: where the interaction of the fast states with the space-charge region can be investigated or in some cases even eliminated.

Another experiment such as the measurements of luminescence together with the field effect will allow us to study the spectral distribution of energy.

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